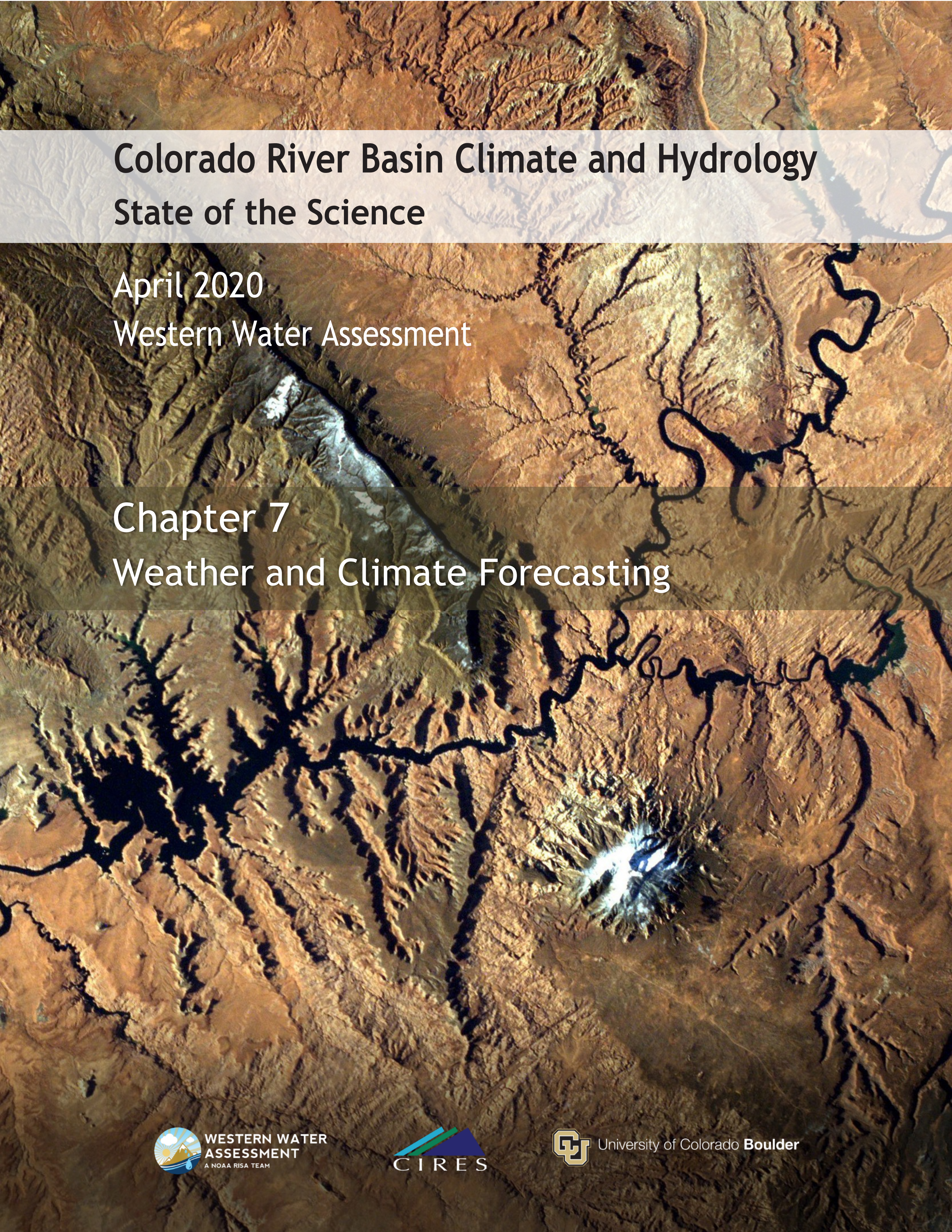


Colorado River Basin Climate and Hydrology

State of the Science

April 2020

Western Water Assessment

Chapter 7

Weather and Climate Forecasting

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

University of Colorado Boulder

Colorado River Basin Climate and Hydrology
State of the Science

April 2020

Editors and Lead Authors

Jeff Lukas, University of Colorado Boulder (CU Boulder), Cooperative Institute for Research in Environmental Sciences (CIRES), Western Water Assessment (WWA)
Elizabeth Payton, CU Boulder, CIRES, WWA

Authors

Stephanie McAfee, University of Nevada, Reno
Andy Wood, National Center for Atmospheric Research (NCAR) Research Applications Lab (RAL)
Connie Woodhouse, University of Arizona, Climate Assessment for the Southwest (CLIMAS)
Ben Harding, Lynker
Lineke Woelders, CU Boulder, CIRES, WWA
Rebecca Smith, Bureau of Reclamation, Lower Colorado Basin Region
Ethan Gutmann, NCAR RAL
Flavio Lehner, NCAR Climate & Global Dynamics Lab, and ETH Zürich
Joseph Barsugli, CU Boulder, CIRES, WWA
Klaus Wolter, CU Boulder, CIRES
Imtiaz Rangwala, CU Boulder, CIRES, WWA, and North Central Climate Adaptation Science Center
Benét Duncan, CU Boulder, CIRES, WWA
Jeff Deems, CU Boulder, CIRES, WWA, and National Snow and Ice Data Center (NSIDC)
Carly Jerla, Bureau of Reclamation, Lower Colorado Basin Region
James Prairie, Bureau of Reclamation, Upper Colorado Basin Region

Available online at https://wwa.colorado.edu/CRBReport

Citation: Lukas, Jeff, and Elizabeth Payton, eds. 2020. *Colorado River Basin Climate and Hydrology: State of the Science*. Western Water Assessment, University of Colorado Boulder. DOI: https://doi.org/10.25810/3hcv-w477.

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

University of Colorado Boulder

Acknowledgements

Sponsors

The authors are grateful for the generous funding, collaboration, and guidance from the water resource managers of the following organizations: the Arizona Department of Water Resources, Bureau of Reclamation, California's Six Agency Committee, Central Arizona Water Conservation District, Colorado River Water Conservation District, Colorado Water Conservation Board, Denver Water, Metropolitan Water District of Southern California, New Mexico Interstate Stream Commission, Southern Nevada Water Authority, Utah Division of Water Resources, and the Wyoming State Engineer's Office. This group of water resource managers is working to advance scientific understanding to improve the accuracy of hydrologic forecasts and projections, to enhance the performance of predictive tools, and to better understand the uncertainty related to future supply and demand conditions in the Colorado River Basin.

Reviewers

We would also like to thank the people who shared their time and expertise reviewing the first draft of this report:

Sponsor reviewers

Representatives of the sponsoring agencies named above

Technical reviewers

Chapter 2
Michael Crimmins, University of Arizona, CLIMAS
Russ Schumacher, Colorado State University, Colorado Climate Center
Brad Udall, Colorado State University, Colorado Water Center

Chapter 3
Cameron Bracken, Bonneville Power Authority
Kevin Wheeler, Water Balance Consulting

Chapter 4
Andrew Newman, NCAR Research Applications Lab
Nancy Selover, Arizona State University, Arizona State Climate Office

Chapter 5
Kat Bormann, Jet Propulsion Laboratory, Caltech and NASA
David Clow, USGS Colorado Water Science Center
Mark Landers, USGS National Streamgage Network Coordinator

Chapter 6
Ben Livneh, CU Boulder, CIRES, WWA and Civil Engineering
Mark Raleigh, CU Boulder, CIRES, NSIDC
Peter Troch, University of Arizona

Chapter 7
Emily Becker, University of Miami, Cooperative Institute for Marine and Atmospheric Studies (CIMAS)
Kathy Pegion, George Mason University
Tom Hamill, NOAA ESRL Physical Sciences Division

Chapter 8
Guotao Cui, University of California, Merced
Kevin Werner, NOAA Northwest Fisheries Science Center

Chapter 9
Upmanu Lall, Columbia University, Columbia Water Center
David Tarboton, Utah State University, Utah Water Research Laboratory

Chapter 10
Toby Ault, Cornell University
Greg Pederson, USGS Northern Rocky Mountain Science Center

Chapter 11
David Pierce, Scripps Institution of Oceanography and California-Nevada Climate Applications Program (CNAP)
Julie Vano, Aspen Global Change Institute

Other contributors

The authors appreciate the following individuals for contributions to one or more sections of the report:

Genevieve Allan, Bureau of Reclamation, Lower Colorado Region
Sarah Baker, CU Boulder, CADSWES and Bureau of Reclamation
Dan Bunk, Bureau of Reclamation, Lower Colorado Region
Alan Butler, Bureau of Reclamation, Lower Colorado Region
Marty Hoerling, NOAA ESRL Physical Sciences Division
John Lhotak, NOAA NWS Colorado Basin River Forecast Center (CBRFC)
Scott McGettigan, Utah Division of Water Resources
Matt Miller, USGS Earth Systems Modeling Branch
Paul Miller, NOAA NWS CBRFC
Naoki Mizukami, NCAR RAL
Balaji Rajagopalan, CU Boulder, CIRES and Civil Engineering
Michelle Stokes, NOAA NWS CBRFC
Sonya Vasquez, USGS
Karl Wetlaufer, NRCS Colorado Snow Survey

Special thanks

We are especially grateful to Ethan Knight, WWA's talented student intern, whose contributions to the report have been enormous and essential. And we deeply appreciate the project coordinating efforts of Seth Shanahan of the Southern Nevada Water Authority and Rebecca Smith of the Bureau of Reclamation, whose responsiveness and good judgment kept us on target. Lisa Dilling, WWA director and CU associate professor of Environmental Studies, also deserves special mention for her support and encouragement throughout the project duration.

Credits

Design and graphics: Ami Nacu-Schmidt, CU Boulder, CIRES, Center for Science and Technology Policy Research

WWA maps of the Colorado River Basin: Lineke Woelders, CU Boulder, CIRES, WWA

Report cover photo: NASA Sally Ride EarthKAM Image Gallery, April 2017 Mission, IMAGE_136343, http://images.earthkam.org/main.php?g2_itemId=762965

Cover page photos for Chapters 1, 2, 5, 8 and 11: Adobe stock

Chapter 3 cover page photo: Clay Banks on Unsplash

Chapter 4 cover page photo: Robert Murray on Unsplash

Chapter 6 cover page photo: Sheelah Brennan on Unsplash

Chapter 7 cover page photo: John Price on Unsplash

Chapter 9 cover page photo: Rainer Krienke on Unsplash

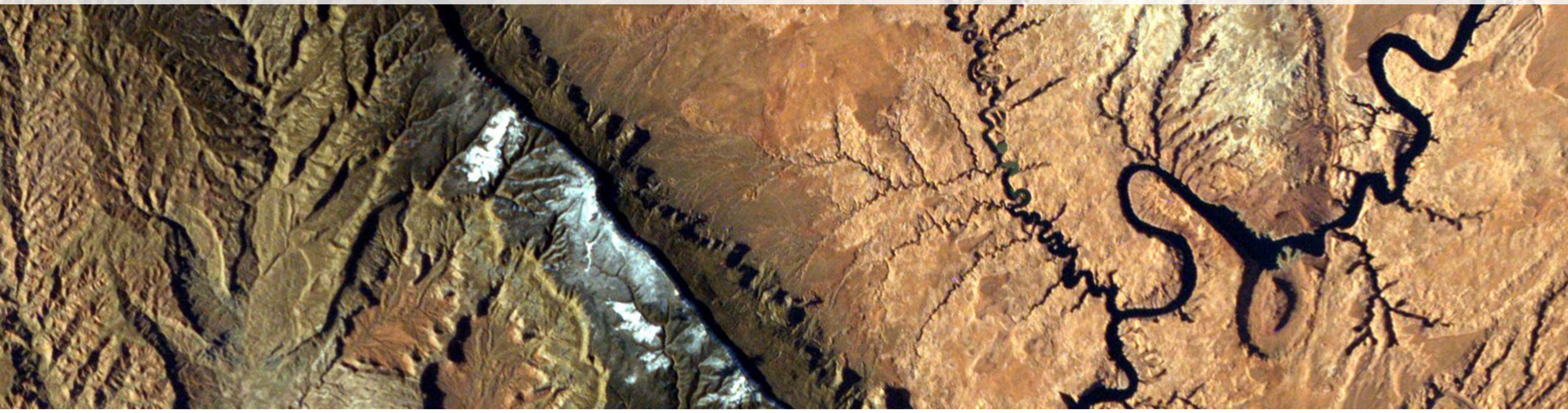
Chapter 10 cover page photo: Grand Canyon National Park, Wikimedia Commons, https://www.flickr.com/photos/grand_canyon_nps/12199509204/

Volume III

Short-term and Mid-term—Informing the 1-Month to 5-Year Time Horizon

Chapter 7. Weather and Climate Forecasting

Chapter 8. Streamflow Forecasting



Volume III of the Colorado River Basin State of the Science report focuses on models and methods for forecasting weather, climate, and streamflow at the short- to mid-term time scale. Forecasts at this time scale are critical to water managers ensuring supply to their customers, farmers making planting decisions, ski areas planning staffing needs, utility operators making purchasing decisions, and retailers trying to plan inventory, among many others.

The two chapters in Volume III offer comprehensive descriptions and assessments of the state of short-to-mid-term forecasting methods, their skill, the data they require, their applications, and their tradeoffs. Results from weather and climate forecasting models feed into streamflow forecasting models to generate forecasted inflows for Reclamation's three primary models.

Chapter 7 describes the methods used to forecast weather and climate. The chapter is organized around the three forecast time frames: weather, 1-14 days; sub-seasonal, 14 days to 3 months; and seasonal, 3 months to 1 year. Weather forecasts are the most skillful of the three, and demonstrate steady, if small, improvements. The most challenging of these time frames is the sub-seasonal time frame; this chapter describes why this is so, and addresses the constraints on future improvements to forecasts on this time frame. Seasonal forecasts perform in the middle—they currently lack skill, particularly for precipitation, but judicious use of these forecasts, at times and places of good predictability, could be beneficial. Accordingly, the bulk of the chapter provides background on the tools and techniques that are behind seasonal forecasts and provides a good reference on the operational seasonal forecast products. The chapter concludes by describing the implications of the current state of seasonal forecasting for the basin, particularly the Upper Basin, and describes initiatives to improve seasonal forecasts. Finally, it surveys the challenges and opportunities for forecasting across all three time frames.

Chapter 8 describes the concepts, approaches and tools used to forecast streamflow. This chapter focuses mainly on techniques and models that are relevant to Reclamation operations and planning activities—the monthly to seasonal ensemble forecasts that provide critical input to Reclamation's 24-Month Study (24MS) and Mid-term Operations Probabilistic Model (MTOM), which are used to generate system operations projections (monthly reservoir releases and storages) up to 5 years out (Chapter 3). The chapter explains the sources of predictability, in order to provide a basis for forming priorities for improvement of forecasts. It describes three types of forecast models, dynamical, statistical, and hybrid; two types of forecasts, single-value and ensemble; and two forecasting paradigms, in-the-loop and over-the-loop. It provides detailed descriptions of operational forecast systems and experimental products across three time frames: short-range (days), mid-range (months) and interannual to decadal (Year 2 and beyond). Then, the use of mid-range streamflow forecasts—the only operational use of streamflow forecasts by Reclamation in the basin—in the 24MS and MTOM is described. Reclamation has considerable immediate interest in improving operational forecasts for Year 2, but decadal climate prediction currently exhibits poor skill, and NWS has not yet made investments toward improving Year 2 predictions. Chapter 8 describes Reclamation's own initiative toward improved Year 2 forecasts, the Colorado River Basin Streamflow Forecast Testbed, intended to provide an objective approach to compare current and experimental streamflow forecasting methods. Finally, Chapter 8 provides a comprehensive review of the benefits, limitations, and challenges of a broad array of potential scientific and technological improvements to the existing operational streamflow forecast systems.

Chapter 7

Weather and Climate Forecasting

Authors

Lead:

Jeff Lukas (CU Boulder, CIRES, WWA)

Contributing:

Klaus Wolter (CU Boulder, CIRES)
Joseph Barsugli (CU Boulder, CIRES, WWA)

Chapter citation:

Lukas, Jeff, Klaus Wolter, and Joseph Barsugli. 2020. "Weather and Climate Forecasting." Chap. 7 in *Colorado River Basin Climate and Hydrology: State of the Science*, edited by J. Lukas and E. Payton, 254-286. Western Water Assessment, University of Colorado Boulder.

Key points

- Uncertainty about upcoming weather and climate conditions translates into a major source of uncertainty in seasonal streamflow forecasts.
- Weather forecasts out to 10 days have relatively high skill and are progressively improving; they are incorporated into the CBRFC's operational streamflow forecasts.
- Sub-seasonal (2 weeks to 12 weeks) and seasonal (3 months to 1 year+) climate forecasts have much lower skill, especially in the Upper Basin, and they are not incorporated in the CBRFC streamflow forecasts.
- A major research effort has ramped up in the last decade to advance sub-seasonal and seasonal forecasting.
- Sub-seasonal and seasonal forecasts for temperature are generally more skillful than forecasts for precipitation, and skill for both is generally higher for the Lower Basin than for the Upper Basin.
- For precipitation, the Climate Prediction Center's seasonal forecast skill in both basins has been positive for winter and spring, suggesting users should focus their forecast use on those seasons.
- There are other opportunities to better utilize the skill that does exist in sub-seasonal and seasonal climate forecasts, such as using them to "nudge" the streamflow forecast ensemble during post-processing.

7.1 Overview

Uncertainty about future weather and climate affects streamflow forecasting on multiple timescales. In particular, uncertainty about the future weather and climate is one of the largest sources of error in seasonal streamflow forecasting. Even if, on April 1, we had perfect knowledge of the snowpack, and knew exactly how much of that snow would be translated into runoff, we would still have considerable uncertainty in spring-summer streamflow forecasts, because the weather that occurs from April through July can have a substantial impact on the runoff over that period.

When weather and climate forecasts have positive skill, i.e., predictive value above and beyond a null forecast (i.e., the climatological average conditions), there is an opportunity to inform and improve streamflow forecasts, and to guide other water resource decision-making. Weather forecasts out to roughly 10 days have relatively high skill for both temperature and precipitation (Figure 7.1), so CBRFC operational water supply forecasts incorporate them, as described in section 7.3.

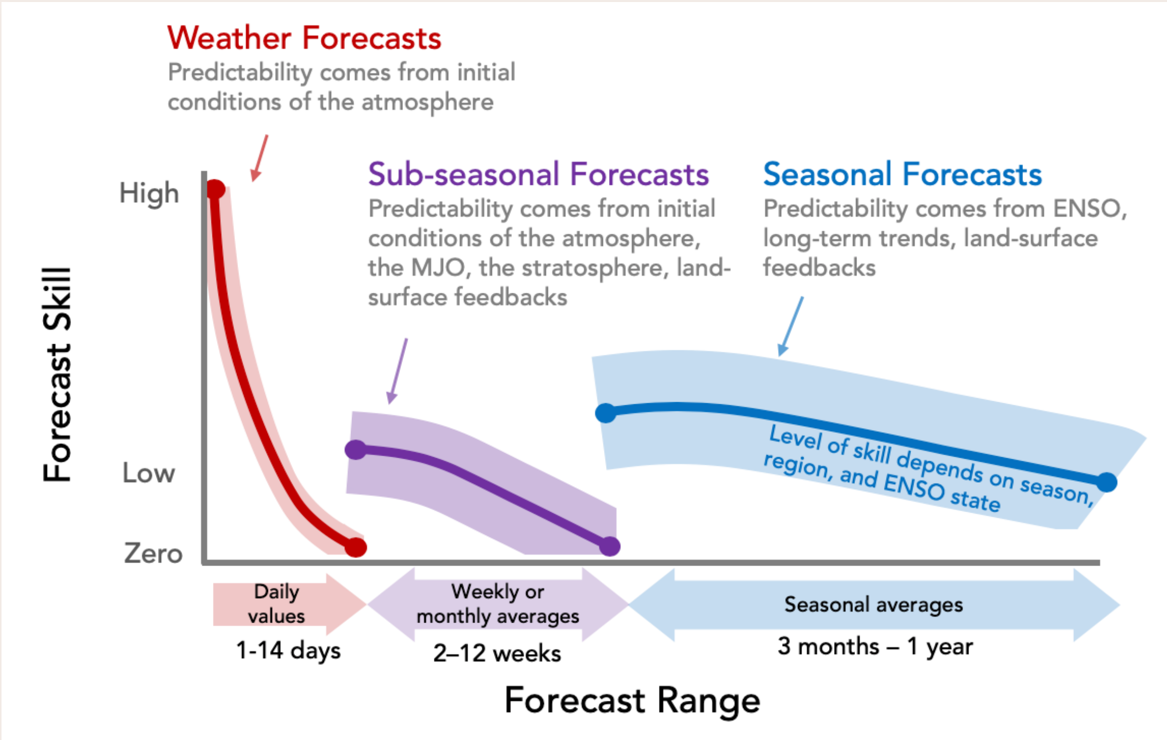


Figure 7.1

Schematic showing typical forecast skill relative to forecast range for three types of weather and climate forecasts: short-range weather forecasts; sub-seasonal climate forecasts, and seasonal climate forecasts, including potential sources of predictability. Relative skill is based on differing forecast averaging periods, shown inside the arrows. (Source: adapted from a figure by Elisabeth Gawthrop and Tony Barnston, International Research Institute for Climate and Society).

At longer sub-seasonal and seasonal climate forecast periods (>14 days), the forecast is generally much lower than the skill for weather forecasts, constraining opportunities for improving streamflow forecasts (Figure 7.1). The CBRFC operational water supply forecasts do not currently incorporate sub-seasonal (2–12 weeks) or seasonal (3 months and longer) climate forecasts, due to their low skill.

The CBRFC's Hydrologic Ensemble Forecast Service (HEFS) system provides a pathway for incorporating additional weather and climate forecasts into their streamflow forecasts, if they have sufficient and consistent skill and an archive of historical hindcasts to allow validation. CBRFC forecasters have tested the incorporation of some sub-seasonal and seasonal climate forecasts, as described below and in Chapter 8.

The overall gap in predictive skill between weather forecasts and longer-term climate forecasts is reflected in fundamental differences in the way the forecasts are presented. First, weather forecasts are for specific daily (or more frequent) outcomes, while sub-seasonal and seasonal climate forecasts are for outcomes as averaged across weekly, biweekly, monthly, or seasonal periods. Second, weather forecasts are usually presented as *deterministic* forecasts: a single temperature value or precipitation amount is forecasted. (The exception is the familiar "probability of precipitation" forecast, e.g., 40% chance of rain tomorrow.) Sub-seasonal and seasonal forecasts are typically presented in *probabilistic* terms, as a shift in likelihood compared to the historical distribution of outcomes, e.g., 60% chance of wetter than normal conditions over the winter season, compared to a 50% chance across the historical period (assuming a 2-category forecast). Sub-seasonal and seasonal forecasts can also be presented as deterministic forecasts (e.g., 2.3" of precipitation over the next 1-month period) but users should be aware that the specificity and precision of such forecasts is far greater than their accuracy and skill.

Increasingly, "S2S" is used as a shorthand for "sub-seasonal to seasonal forecasts," but the actual forecast periods being referred to can be inconsistent. In most technical literature, S2S refers to sub-seasonal forecasts; i.e., forecast periods up to one season (<3 months). But S2S has also been used to refer to sub-seasonal *and* seasonal forecasts, or, less frequently, sub-seasonal *and* season 1 (i.e., 3-month) forecasts. To avoid confusion, in this chapter we use the terms "sub-seasonal" and "seasonal" instead of S2S, except when the latter is part of the name of a project.

7.2 What makes a weather or climate forecast useful?

First, a distinction needs to be made between forecast *quality*, which is assessed independently of the use of the forecast, and forecast *value*, which is the utility of the forecast to the user.

The assessment of forecast quality—verification—has several components. The measures of quality need to be evaluated across many (100s or 1000s) forecasts produced by the same forecast *system* in order for the measures to be taken as indicative of the quality of current or forthcoming forecasts that have not yet been verified (Hudson 2017), which is what the user really wants to know.

- *Accuracy* is the overall level of agreement between the forecasted and predicted values. But accuracy by itself can be misleading, since a "naïve" forecast can be quite accurate. For example, since precipitation occurs on only 20-30% of all days in most locations in the Upper Basin, a consistent daily forecast of "no precipitation" will be accurate 70-80% of the time.
- *Skill* is more meaningful than accuracy; it measures the accuracy of the forecast relative to a baseline "naïve" forecast: the climatological value,

a simple persistence forecast, or, if there are multiple forecast "bins," the odds of forecasting the correct bin by chance alone. Positive skill (>0 for nearly all skill metrics) means that there is value beyond the naïve forecast. There are many different metrics of forecast skill; the metrics shown in the figures and tables below, and explained in the text, are the anomaly correlation (AC) and Heidke skill score (HSS). Both are fairly simplistic and cannot by themselves convey the multiple dimensions of forecast quality, or the forecast's value to the user.

- *Reliability* is a measure of forecast quality specific to probabilistic forecasts; it is the agreement between the forecast probability and observed frequency of outcomes. For example, across all of the days a weather forecast system called for a 30% chance of rain, for perfect reliability it would have rained on 30% of those days, and so on for other percentages. Reliability can likewise be measured for sub-seasonal and seasonal forecasts; e.g., across all the 3-month seasons for which a climate forecast system called for a 60% chance of above-normal precipitation (assuming only two categories, above and below), then for perfect reliability, 60% of those seasons should have observed above-average precipitation, and so on.
- Additional measures of skill specific to probabilistic forecasts complement reliability. *Resolution* measures how well the forecasts can distinguish different categories; e.g., do the observed outcomes differ between periods with forecasts of 60% chance of above-normal precipitation and with forecasts of 70% chance of above-normal precipitation. *Sharpness* is the ability to forecast extreme values (probabilities near 0% or 100%) in at least some cases, rather than only values clustered around the observed mean probability.

Broadly speaking, the higher the forecast quality, the more opportunity there is for the forecast to be useful, but forecast quality and value to the user are not necessarily linked (Hudson 2017). Usefulness also strongly depends on the decision context, including the risk tolerance of the user, and whether the forecast is used in a decision-support tool (e.g., a streamflow forecast model) or considered on its own.

Deterministic weather forecasts out to 5–10 days have become skillful enough that the forecasted conditions can be treated as though they *will* occur, such as with the incorporation of weather forecasts into the CBRFC ESP water supply forecasts (see section 7.3). Water managers often use weather forecasts to make discrete, yes-or-no decisions with some confidence, e.g., releasing water from a nearly full reservoir now to avoid an uncontrolled spill a week from now, given the forecast of heavy rainfall over the next five days.

Sub-seasonal and seasonal climate forecasts will never have that level of skill or certainty; relatively low predictability at these time scales may be a fundamental property of the climate system (Albers and Newman 2019). But if climate forecasts have at least *some* positive skill or reliability for the basin and season of interest, they can potentially be useful. Since climate forecasts are typically presented in probabilistic terms, they are suited for modeling and decision support frameworks that are themselves probabilistic, such as ensemble streamflow prediction. In this case, the tendency shown in the climate forecast, if any (e.g., 60% chance of above-normal precipitation), can be used to weight the historical years used to populate the streamflow ensemble.

Climate forecasts can also be used to inform discrete, infrequent yes-or-no decisions, such as whether to generate hydropower during the fall and winter instead of maximizing water storage, but decision makers must accept the significant risk of the forecasted climate tendency not actually occurring (Garbrecht and Piechota 2005). Also, there may not be a large enough forecasted tendency in a given year or season to influence a decision. In many contexts, then, climate forecasts may provide more value when used selectively, rather than routinely.

7.3 Weather forecasts (1 to 14 days out)

The steady progress in weather forecasting over the last several decades has been called a "quiet revolution," resulting from a steady accumulation of knowledge about the atmosphere and technical advances in modeling. Forecast skill for the mid-latitude regions in the Northern Hemisphere, such as over the Colorado River Basin, has been increasing by about 1 day per decade for forecast lead times of 3 to 10 days; today's 5-day weather forecast is as skillful as the 4-day forecast was 10 years ago (Bauer, Thorpe, and Brunet 2015).

The main source of predictability and skill for weather forecasts is the accurate description of the initial conditions of the atmosphere (Figure 7.1) by coordinated global networks of observations from sensors that are land, ocean, and satellite-based, and from airborne sensors. Once initialized with those observations, the weather forecast model simulates the evolution of the initial synoptic (large scale) weather patterns shown in the observations. The skill of weather forecasts, on average, systematically declines from day 1 to day 14 (Figure 7.1) as the information contained in the initial conditions is gradually lost to chaotic processes underlying the motions of the atmosphere. This information loss can be slowed by improved initialization of the models (i.e., better observations), and by improved modeling of the physical processes, but a marked drop-off in skill during weeks 1 and 2 will persist through any conceivable future improvements. Producing moderately skillful forecasts at longer lead times (i.e., sub-seasonal) requires additional information beyond weather patterns and associated atmospheric motions, such as the correct prediction of changes in the stratosphere, persistence due to land surface conditions, and slowly varying ocean-atmosphere patterns (e.g., Madden-Julian Oscillation, or MJO; and El Niño-Southern Oscillation, or ENSO).

All operational weather forecasts are based on dynamical, physics-based simulation models that run on supercomputers; thus, weather forecasting is also referred to as numerical weather prediction (NWP). The domain of most weather models is global, though very-high-resolution weather models (e.g., Weather Research and Forecasting model, WRF), with regional domains such as the western U.S., are also used for short-term forecasts of 48 hours or less.

The domain of all weather and climate models is gridded in three dimensions, with the vertical dimension representing multiple layers of the atmosphere. The models solve the fundamental physical equations for fluid motion; conservation of mass, momentum, and energy; and the ideal gas law. Many relevant processes occur at scales smaller than the model grid, such as cumulus cloud formation, so parameterization schemes are needed to properly describe the impact of these sub-grid-scale mechanisms on the large-scale flow of the atmosphere (Bauer, Thorpe, and Brunet 2015). The initialization of the forecasts with observations is accomplished through data assimilation, which typically involves the statistical correction of a prior short-term gridded model forecast to the newly available observations, in order to provide the most accurate gridded depiction of the initial state.

The primary global weather forecast models used in operational weather forecasts in the U.S. include the NOAA National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model, the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) model (often referred to as the "European model"), and the Global Environmental Multiscale (GEM) model (the "Canadian model").

The evolution of weather patterns over time is highly sensitive to the initial state of the atmosphere, and we cannot observe and describe those initial conditions perfectly. Consequently, it has become common to run a set, or ensemble, of weather predictions from the same model using slightly different initial conditions. The spread of the forecasts in the ensemble thus captures the uncertainty due to our imperfect knowledge of initial conditions. The NOAA Global Ensemble Forecast System (GEFS) based on the NOAA GFS forecast model is made up of 21 separate forecasts (ensemble members), with output four times a day and forecasts going out to 16 days. The ECMWF Ensemble Prediction System comprises 51 forecasts from the ECMWF forecast model using different initial conditions, like GEFS, and also with slightly different model equations to represent uncertainty due to model structure and parameters (see discussion of uncertainty in Chapter 1).

Even with recent technical progress, these ensemble prediction systems for weather (and climate) forecasts inevitably have some bias (the forecasted mean is different from the observed mean) and unreliability (the forecasted distribution is different from the observed distribution). Thus, statistical post-processing of "raw" forecasts, to improve ensemble forecast guidance prior to its dissemination, is a critical element of the forecast process. The discrepancies between past forecasts and observations are used to adjust the raw real-time forecasts.

Skill of forecasts over weather timescales

Table 7.1 shows the skill of weeks 1 and 2 forecasts of precipitation and temperature for the Upper and Lower Basins from the NOAA NCEP CFSv2 (Climate Forecast System) model. The skill metric (Anomaly Correlation Coefficient; ACC) compares the 14-day average forecasted precipitation and temperature with the observed 14-day averages. As noted earlier, and shown in Figure 7.1, the skill drops off rapidly within that 14-day period, and the skill would be substantially higher if the results were only for week 1.

Table 7.1

Skill (Anomaly Correlation; AC) for weeks 1–2 (1–14 days out) of deterministic forecasts from the CFSv2 model for the calendar year (annual) and the climatological seasons, based on reforecasts for the 1999–2010 period. A perfect forecast would have an AC skill of 1.0; the climatological average has a skill of 0. The skill scores for the eight HUC4 sub-basins each in the Upper Basin and Lower Basin were averaged to produce the scores shown here. The CFSv2 forecasts were bias-corrected using quantile mapping. (Data: S2S Outlooks for Watersheds; http://hydro.rap.ucar.edu/s2s/)

Skill (AC) for Weeks 1-2 forecasts, CFSv2 model						
Variable	Basin	Annual	DJF	MAM	JJA	SON
Precipitation	Upper Basin	0.59	0.70	0.56	0.51	0.57
	Lower Basin	0.67	0.77	0.59	0.58	0.58
Temperature	Upper Basin	0.77	0.74	0.78	0.77	0.79
	Lower Basin	0.80	0.79	0.81	0.74	0.80

The forecast skill is generally high (about 0.6–0.8), with overall higher skill for temperature forecasts than precipitation forecasts. This disparity in forecast skill between temperature and precipitation is seen across longer time scales as well, which reflects that temperature varies less than precipitation over both time and space, and is also more straightforward to simulate and predict. Table 7.1 also shows that Lower Basin precipitation forecasts are somewhat more skillful than those for the Upper Basin, and that precipitation forecast skill in both basins is higher in winter than in other seasons. Predictive skill for precipitation also has strong seasonal patterns; skill is highest in winter, reflecting that the primary mechanism of precipitation (mid-latitude cyclonic storms) is broader scale and better simulated than convective precipitation in the warmer seasons.

CFSv2 is a fully coupled climate forecast model that incorporates the GFS weather forecast model (run at lower resolution than for weather forecasting) to represent atmospheric motions, an ocean model, and the Noah land surface model (Chapter 6). We show the skill of CFSv2 for weather timescales (weeks 1–2), instead of that of the GFS or another dedicated weather forecast model, to allow direct comparison with the skill (i.e., ACC) of the same CFSv2 model over sub-seasonal timescales (weeks 3-4) later in this chapter (Table 7.2). The skill of the operational GFS model over this time period would be higher than CFSv2 due to its higher spatial resolution and more optimized capture of initial conditions.

As mentioned above, the skill of weather forecasts has been increasing at a fairly constant rate over the past 20 years, as many improvements have been made in observing systems, assimilation schemes, and the models themselves. There may be an opportunity for CBRFC streamflow forecasts to incorporate weather forecasts, especially for precipitation, at longer lead times than is currently done.

Current use of weather forecasts by the CBRFC

Currently, the CBRFC ESP water supply forecasts that are key inputs to the 24MS and MTOM models (Chapter 3) use two types of weather forecasts: the 10-day quantitative temperature forecast (QTF) and the 5-day quantitative precipitation forecast (QPF). The temperature forecasts come from the National Blend of Models (NBM), a nationally consistent suite of calibrated forecast guidance based on a blend of both NOAA and non-NOAA weather model data. The precipitation forecasts are based on the NBM and additional guidance from the NOAA Weather Prediction Center. The forecast grids are modified by the CBRFC to allow for their incorporation into the CBRFC streamflow forecast model (Chapters 6 & 8).

The QPF predicts a specific, most-probable amount of precipitation that will fall over the forecast period; i.e., it is presented as a deterministic forecast. Because these short-term forecasts of precipitation have high skill, the CBRFC forecast model treats the QPF as though it represents precipitation that has already fallen. When a storm is forecasted to hit the basin within 1–5 days from the issuance of an ESP or official streamflow forecast, the forecasted storm as shown in the QPF will cause an increase in the forecasted seasonal streamflow volume, even though the storm has not yet arrived. Likewise, if the QTF shows an unusually warm period in mid-winter, the CBRFC model can reduce the modeled lower-elevation snowpack and thus decrease the forecasted streamflow volume. Thus, over the course of a season, a trace created by the most-probable ESP forecasts incorporating the QPF (and QTF) consistently leads, by up to 5 days, a trace created by ESP forecasts without the QPF, while having similar fluctuations reflecting storms and melt episodes (Figure 7.2).

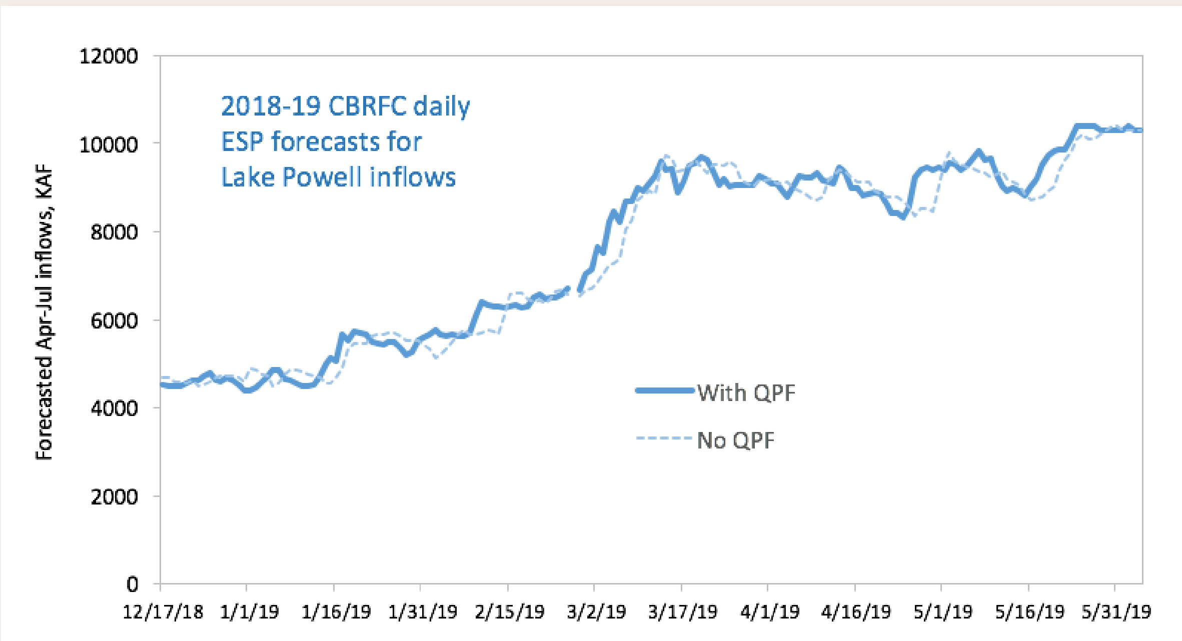


Figure 7.2

CBRFC daily ESP forecasts for April–July Lake Powell inflows for the 2018–2019 season issued from mid-December through early June. The default forecasts ("With QPF") that incorporate 5-day Quantitative Precipitation Forecasts (QPF) and 10-day Quantitative Temperature Forecasts (QTF) show increases in forecasted streamflow volumes about 2–5 days before forecasts with no QPF, reflecting the expected gains from forecasted storms that have not yet occurred. (Data: CBRFC)

7.4 Sub-seasonal forecasts (2 weeks to 12 weeks)

Overview

For the purposes of this section, "sub-seasonal" refers to forecasts of meteorological variables at lead times from 2 weeks to 12 weeks in the future. This period has been called the "weather-climate prediction gap" (Mariotti, Ruti, and Rixen 2018). Short-term weather forecasts depend crucially on the initial state of the atmosphere that is input to the forecast models, while longer-term seasonal climate forecasts leverage predictability that emerges from the slower-evolving components of the Earth system including the ocean state, soil moisture, sea-ice conditions and other so-called "boundary conditions" for the atmosphere (Figure 7.1). The sub-seasonal prediction gap—where both initial and boundary conditions can be important—is being closed, albeit slowly, from both sides. The first two months of seasonal climate forecasts provides information about this time frame, while medium-range weather prediction models such as NOAA's GFS and the ECMWF's IFS are being extended out to 30–45 day forecasts and beyond.

The dynamical models used for sub-seasonal (and seasonal) predictions are typically run at lower resolution than for weather forecasts. They simulate the interactions between the atmosphere, ocean, land surface, and sometimes sea ice components of the climate system. While it is common to differentiate "climate models" from "weather models," these two categories overlap a great deal, especially for the models used at a sub-seasonal time scale—some of which are also used for weather forecasts, while others are also used for multi-decadal climate projections (i.e., GCMs; Chapter 11).

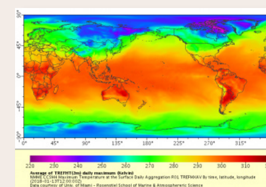
When current generation weather forecast models (e.g., GFS, ECMWF IFS) are extended beyond 14 days, they develop large systematic forecast errors, particularly in their representation of tropical convection and the positioning of the mid-latitude jet stream and storm track (World Meteorological Organization 2013). Similarly, climate forecast models such as NOAA's CFSv2, which are better tuned to reduce bias in the climatological (long-term average) atmospheric circulation, tend to have lower performance for short lead times (0–7 days) than the weather models. This lower performance is due to many factors: coarser spatial resolution, biases that appear in the oceanic and land surface components, and the fact that the atmospheric and oceanic initial conditions are not optimized as they are for weather models. An active area of research is to better incorporate data from the atmosphere, land, ice, and oceans into the initial conditions of forecast models, referred to as "coupled data assimilation" (World Meteorological Organization 2017).

Sub-seasonal forecasting also faces a statistical disadvantage compared to seasonal forecasts. Because the forecast periods for the sub-seasonal forecasts are shorter than the 3-month season that is the typical period for seasonal forecasts, there is less time for the unpredictable component of the climate ("noise") to be averaged out.

Note, also, that sub-seasonal forecast skill quoted for periods such as "weeks 1–2" or "weeks 2–3" will be dominated by the weather forecast skill for the early part of that period (Figure 7.1). The same is true for the Climate Prediction Center (CPC) revised monthly forecasts that are issued with no lead time, i.e., on the last day of the month preceding the forecasted month, as opposed to the initial forecasts issued with 8–14 days lead time (See "NOAA CPC Outlooks" below).

Sub-seasonal forecasts of temperature and precipitation are inherently suited for probabilistic interpretation and analysis. Accordingly, ensembles of numerical weather and climate prediction model forecasts are the tools of choice. Such ensembles may be generated by multiple runs of a single forecast model, which accounts for the uncertainty due to our imperfect knowledge of the initial state of the atmosphere. Ensembles can also be comprised of multiple runs from different models, such as with the North American Multi-Model Ensemble (NMME); in this case the ensemble also captures the uncertainty due to model structure and parameters, similar to the CMIP (Coupled Model Intercomparison Project) ensembles of multi-decadal climate projections (Chapter 11). The NMME, which is used for both operational sub-seasonal and seasonal forecasting consists of seven models in total: CFSv2, two Canadian models (CanCM4 and GEM-NEMO), two NOAA GFDL models (CM2.1 and FLOR), NCAR's CCSM4, and NASA's GEOS S2S. Studies have shown that the ensemble-average forecasts from NMME are more skillful than those from any single model in the ensemble (Becker, Van den Dool, and Zhang 2014; Kirtman et al. 2014).

NMME Models and Variables Summary



Link: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-multi-model-ensemble

An effort to generate and archive real-time and retrospective ensembles of sub-seasonal forecasts (SubX; Pegion et al. 2019), similar to NMME, is described below under "Other activities to improve sub-seasonal forecasts."

Sources of predictability

The past decade has seen much progress in identifying and quantifying potential sources of sub-seasonal prediction skill (Vigaud, Robertson, and Tippett 2017), fueling a broad and active research program on sub-seasonal forecasting (e.g., National Academies 2016; World Meteorological Organization 2013). For the continental U.S., the potential sources of skill with the most promise are the tropical Madden-Julian Oscillation (MJO) (Stan et al. 2017), stratospheric variability, and land-atmosphere coupling, including the role of soil moisture. The identification of these phenomena is important because improvement in their representation in climate models can lead to improvement of sub-seasonal temperature and precipitation forecasts. A technical overview of the current state of the science is found in the volume edited by Robertson and Vitart (2019).

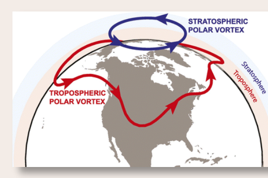
The MJO is a large area of enhanced convection (i.e., thunderstorms) in the tropical Indian and Pacific Ocean that generally moves from west to east (Zhang 2013 and references therein) and recurs with an irregular 40–70 day time period. Numerical models have limited success at forecasting the progression of convection associated with the MJO. Some of the strongest associations of the MJO with precipitation in the United States are seen in California and along the west coast of the U.S. during the wintertime (Zhou et al. 2012), including an effect on atmospheric rivers (Guan et al. 2012). While the impacts of the MJO in the interior West are less than those on the West Coast, the storms of early March 2019 demonstrated that atmospheric rivers can bring substantial precipitation to the Colorado River Basin.

Certain stratospheric phenomena have also been identified as a potential source of skill for weather forecasting on sub-seasonal scales (Robertson and Vitart 2019). The stratosphere is the layer of the atmosphere that lies above the troposphere and is very stable, that is, resistant to vertical motions such as convection. In the mid-latitudes, the lower boundary of the stratosphere lies at about 10 km above the surface, but this boundary can be as high as 20 km in the tropics and as low as 7 km in the polar winter. There are two stratospheric phenomena of particular interest for sub-seasonal prediction: the quasi-biennial oscillation (QBO) in the tropics, where the winds above the tropical tropopause change direction in a roughly 26-month repeating cycle, and variations in the stratospheric polar vortex, including stratospheric sudden warming (SSW) events. See Waugh, Sobel, and Polvani (2017) for a primer on the “polar vortex.”

It is hypothesized that the changing winds due to the QBO may modulate the ability of tropical convection to influence the mid-latitude storm track and hence precipitation over the western U.S. For example, there is some indication that the QBO along with the MJO (see above) may jointly provide increased skill in predicting atmospheric river activity (Mundhenk et al. 2018). For the polar SSWs, the influence is more directly felt on the northern edge of the storm tracks and there is empirical evidence that in the days and weeks after a SSW there is a greater likelihood of extreme cold events (Kidston et al. 2015). However, the surface influence of the SSW appears to be primarily focused in Eurasia and the eastern United States, not in the Colorado River Basin.

A better representation of the land surface and its interactions with the atmosphere is another potential source of forecast improvement on

What is the Polar Vortex and How Does it Influence Weather?
Waugh, Sobel, and Polvani (2017)



Link: https://journals.ametsoc.org/doi/10.1175/BAMS-D-15-00212.1 sub-seasonal time scales, and one particularly relevant to the Colorado River Basin. Most attention here is focused on the role of soil moisture—both better estimation of the initial state of the soils, and better simulation of the evolution of soil moisture anomalies. For sub-seasonal forecasts, soil moisture has two primary effects: It can reduce surface temperature by directing more of the incoming solar energy to evaporation rather than heating, and it can serve as a source of moisture to the atmosphere (Koster et al. 2011; Dirmeyer and Halder 2016). The research has tended to focus on summer conditions as that is when the impacts of soil moisture are thought to be greatest. Indeed, the impacts of having accurate soil moisture conditions were shown to be primarily for temperature.

In the Colorado River Basin and arid West, including initial soil-moisture states in the forecast model enhanced sub-seasonal temperature forecast skill, particularly when soils were wetter than average (Koster et al. 2011). For precipitation, increased forecast skill by including soil-moisture states was seen in the upper Great Plains, but not elsewhere. Correlations also have been found between soil moisture and the onset of the North American Monsoon; the hypothesized mechanism is that wet soils delay the seasonal heating of the land surface which is necessary to drive the land–ocean temperature gradient that then initiates the monsoon (Grantz et al. 2007). Accordingly, better treatment of soil moisture in forecast models may benefit summer precipitation forecasts in the Lower Basin. Simulation of the snowpack in forecast models could also result in improved sub-seasonal to seasonal forecasts both due to the direct effect of snow on surface temperature, and to the delayed impact on soil moisture during and after the snowmelt season.

Finally, ENSO's influence is present on the sub-seasonal time scale, as well as on longer time scales (see Chapter 2). Convection in the tropical Indian and Pacific Oceans has a significant influence on precipitation and temperature in the western United States. Ocean temperature anomalies associated with ENSO also lead to tropical convection anomalies that in turn alter the position and activity of the storm track in the Pacific. While ENSO is usually associated with seasonal forecasts (see next section), it also influences the likelihood of temperature and precipitation anomalies on sub-seasonal scales. As detailed in Chapter 2, those influences are stronger in the Lower Basin than the Upper Basin.

Operational sub-seasonal forecast products

NOAA CPC outlooks

There are relatively few operational forecasts from NOAA in the sub-seasonal time frame, reflecting the less mature state of sub-seasonal climate forecasting relative to weather forecasting, and even relative to seasonal climate forecasting. They are described here. First, NOAA CPC produces an operational, 2-category (above or below normal), probabilistic temperature outlook for weeks 3–4 (Figure 7.3, left). The outlook is based on a blend of dynamical forecast model output, including CFSv2, ECMWF, and the SubX model ensemble, as well as the statistical (or empirical) tools also used for the CPC seasonal outlooks (Table 7.3). Reforecasts may also be used to adjust model output.

The quantity shown in these maps (Figure 7.3) is interpreted as the probability of the average temperature for days 15–30 being above or below the 1981–2010 observed average for that two-week period. For locations where it is impossible to assign any odds, "EC" or "equal chances" is indicated. In contrast, the 6–10 day and 8–14 day outlooks, as well as the seasonal outlooks, are 3-category, tercile forecasts (above normal, near normal, and below normal). NOAA CPC also produces a two-category precipitation outlook for weeks 3–4 (Figure 7.3, right), but this outlook is labeled "experimental" because little skill has yet been demonstrated.

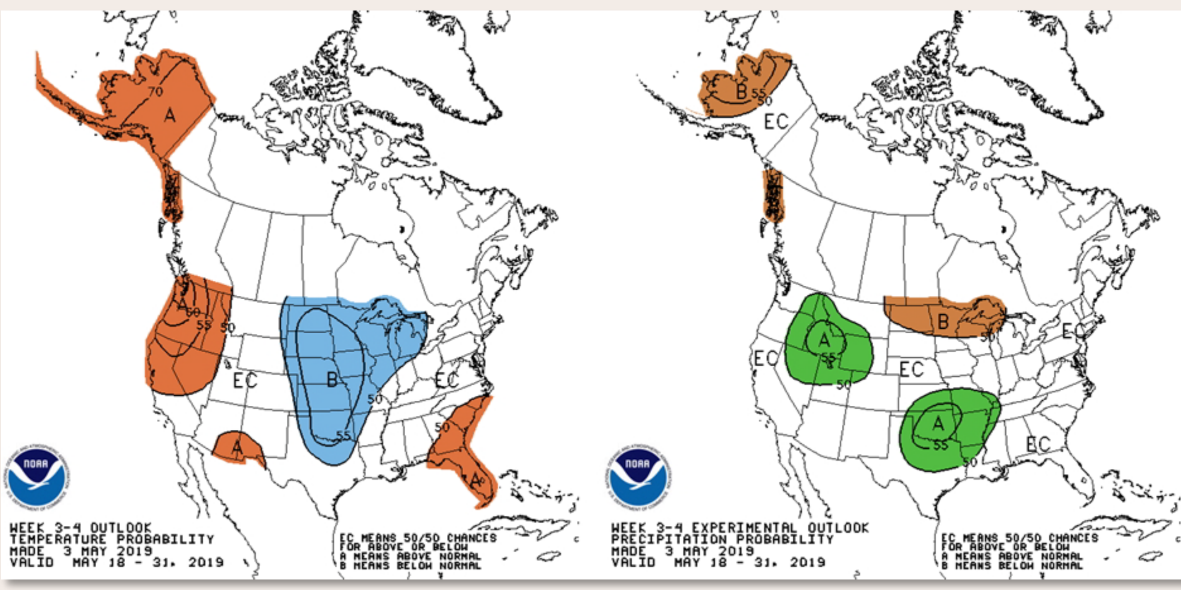


Figure 7.3

NOAA CPC operational 2-category (above or below normal) probabilistic temperature outlook for weeks 3-4 (left) and experimental 2-category (above or below normal) probabilistic precipitation outlook for weeks 3-4 (right). (Source: NOAA CPC; https://www.cpc.ncep.noaa.gov/products/NMME/)

NOAA CPC also produces operational 30-day temperature and precipitation outlooks (Figure 7.4), likewise based on a blend of dynamical forecast models (NMME ensemble—see next section; CFSv2 and ECMWF) and statistical tools and trends. These are issued mid-month, with a "valid" period starting at the beginning of the next month (0.5 month lead). With that 2-week lead time, weather forecast skill is not included in the outlooks. Updated 30-day outlooks are issued at the end of the month (0-month lead), which do incorporate weather forecast information for weeks 1-2, though updated NMME information is not available.

Finally, a 90-day (3-month) average seasonal forecast is also made (as discussed in more detail in the next section), with a 2-week lead time (0.5 month lead). For each of these forecast periods, CPC provides a discussion of the reasoning behind each forecast, including factors such as the MJO and soil moisture, as well as a discussion of the guidance from dynamical models, including those archived in SubX.

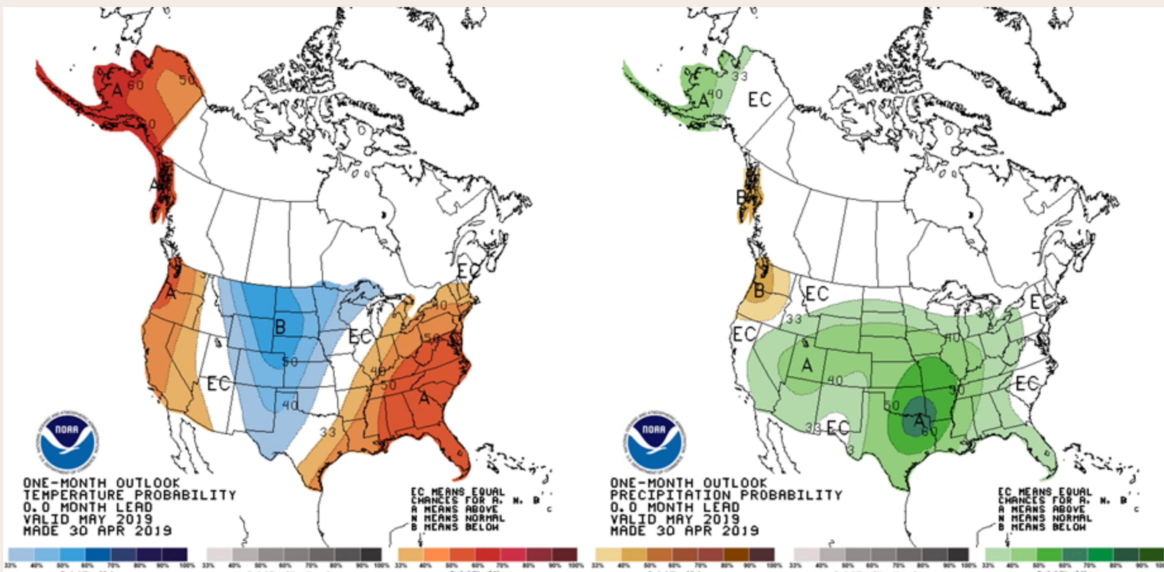


Figure 7.4

NOAA CPC operational 3-category (above or below normal) probabilistic outlooks for month 1 for temperature (left) and precipitation (right). (Source: NOAA CPC; https://www.cpc.ncep.noaa.gov/products/predictions/30day/)

Assessing forecast skill for sub-seasonal (and seasonal) forecasts

A single probabilistic forecast cannot, in general, be verified or falsified. But we can evaluate the performance of the forecast *system* by comparing a set of many forecasts over a period of years with observations, and by deriving statistical metrics of skill. These skill estimates are based on the performance of the forecast system in the past, or of a set of hindcasts that have been produced as if the current system had been operating over that period. This information can guide users about the expected performance of the forecasts of the future, but past performance is no guarantee of the same skill continuing into the future (Weisheimer and Palmer 2014).

In general, the skill of climate forecasts varies much more over space and time than does the skill of weather forecasts (Mariotti et al. 2020). Importantly, some seasons are more amenable to skillful forecasts than others, and this will be noted in the text and tables below. There has also been recent progress in identifying, in real-time, windows of opportunity during which climate forecasts are more likely to be skillful—i.e., times when there are particularly large events in the tropics (MJO, ENSO) or the stratosphere that are likely to have a large imprint in the weather of the extratropics, including the western U.S. (Albers and Newman 2019; Mariotti et al. 2020).

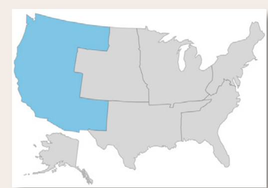
Skill of CPC week 3-4 forecasts for CONUS

Skill evaluation for the CPC weeks 3-4 operational outlooks is available only in aggregate for the conterminous United States (CONUS). In the Heidke skill score (HSS), 100 is a perfect forecast, -50 is a completely incorrect forecast, and a score above 0 indicates skill versus a random forecast. Over the 4-year period from September 2015 to May 2019, the Heidke skill scores for the CPC weeks 3-4 outlooks for CONUS averaged about 40 for temperature, and about 10 for precipitation.

Skill of CPC 30-day forecasts for CONUS and the basin

The skill of the CPC operational 30-day forecasts (at 0.5 month lead time) can be explored using CPC's interactive Verification Web Tool. The skill (HSS) of the temperature forecasts CONUS-wide has averaged about 10 since 2015, though higher, averaging about 20, since 2015. The precipitation forecasts have had no skill, on average, since 2005 (HSS = ~0), with no improvement in recent years. Across the Upper Basin states of Utah, Wyoming, and Colorado, the 30-day temperature forecasts have been more skillful than for CONUS (HSS = 24 since 2005; HSS = 28 since 2015).The precipitation forecasts for Utah, Wyoming, and Colorado have been more skillful than for CONUS (HSS = 7 since 2005), and skill has not increased over time.

CPC Verification Web Tool



Link: https://vwt.ncep.noaa.gov/

Skill of CFSv2 model forecasts for the Colorado River Basin

As described above, the CFSv2 model forecasts are one of the tools used as guidance for the CPC sub-seasonal forecasts. We show the skill of CFSv2 alone to allow comparison with the skill of the model over the weather forecast period (Table 7.1). In general, the AC skill of weeks 3-4 forecasts (i.e., for 15–28 days out) from the CFSv2 model is low (<0.2) for both precipitation and temperature in the Upper and Lower Basins (Table 7.2). Skill is generally lower in the Upper Basin, especially for precipitation (<0.1), perhaps reflecting the weaker ENSO signal there.

Table 7.2

Skill (Anomaly Correlation; AC) for week 3-4 (15-28 days out) forecasts from the CFSv2 model for the calendar year (annual) and the climatological seasons, based on reforecasts for the 1999-2010 period. The skill scores for the eight HUC4 sub-basins each in the Upper Basin and Lower Basin were averaged to the basin-wide scores shown here. The CFSv2 forecasts were bias-corrected using quantile mapping. (Data: S2S Outlooks for Watersheds; http://hydro.rap.ucar.edu/s2s/)

Skill (AC) for Weeks 3-4 forecasts, CFSv2 model						
Variable	Basin	Annual	DJF	MAM	JJA	SON
Precipitation	Upper Basin	0.09	0.09	0.07	0.11	0.10
	Lower Basin	0.16	0.18	0.11	0.13	0.14
Temperature	Upper Basin	0.16	0.22	0.03	0.22	0.18
	Lower Basin	0.18	0.23	0.10	0.23	0.21

S2S Climate Outlooks for Watersheds

The "S2S Climate Outlook for Watersheds" effort is a collaboration between NCAR, CU Boulder, Reclamation, and NOAA CPC to improve the understanding and application of sub-seasonal climate forecast products in the hydrology and water management sector, and to test the capacity to generate new forecast products (Baker, Wood, and Rajagopalan 2019). The map-based web tool (Figure 7.5) shows real-time forecasts from CFSv2 with additional post-processing, and also real-time forecasts from the NMME ensemble. (Again, CFSv2 and NMME output are key elements of the operational CPC weeks 3–4, monthly, and seasonal outlooks, but the CPC outlooks incorporate additional guidance.) Reforecasts have been generated from both sets of models to allow for verification and skill assessment.

The web tool displays deterministic (single-value) precipitation and temperature forecasts from CFSv2 for weeks 1–2, weeks 2–3, and weeks 3-4, and from the NMME for forecasts of 1-month periods at 3 different lead times: 0, 1 month, and 2 months. The forecasted values are expressed in anomalies to allow users to more easily assess whether conditions are expected to be above or below normal. The interface allows users to select any HUC4 watersheds, including the 8 sub-basins of the Upper Basin and the 8 sub-basins of the Lower Basin, and see the forecast values (and skill scores) specific to that watershed. The tool allows users to view the ensemble average of the NMME, as well as the seven model outputs individually; toggling between the outputs of the individual models provides some sense of the uncertainty in the forecasts.

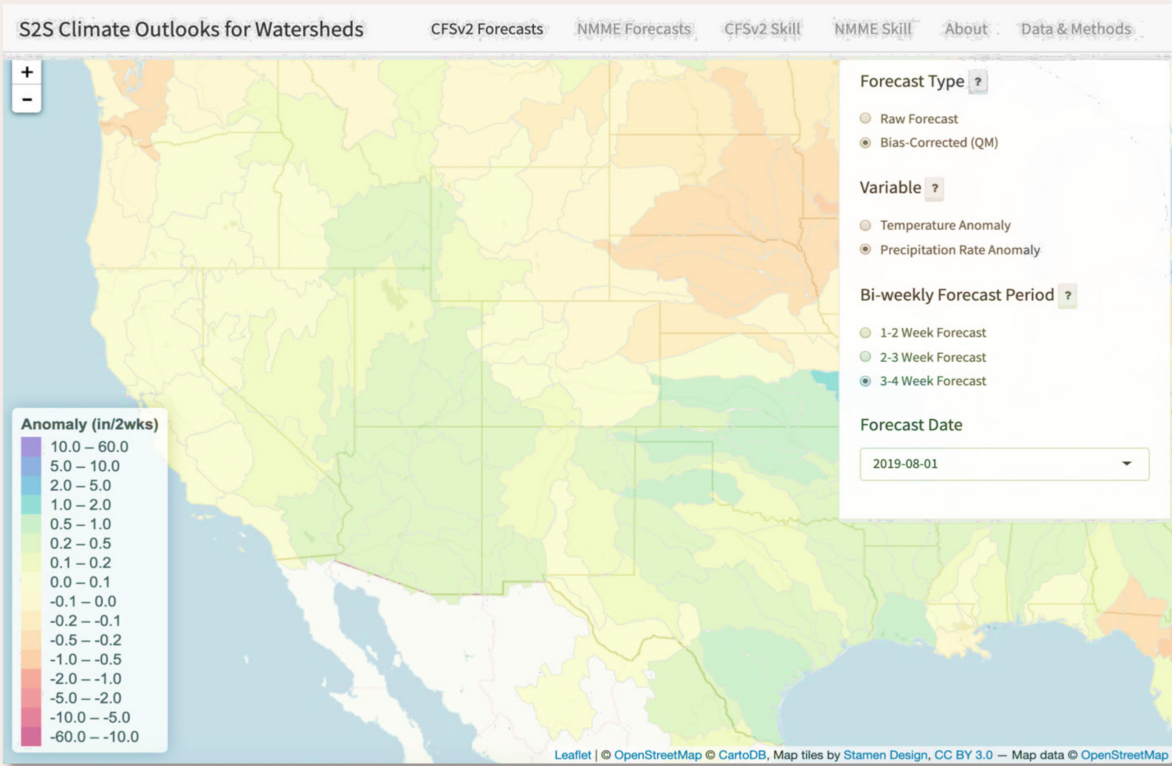


Figure 7.5

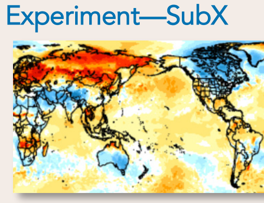
The S2S Climate Outlooks for Watersheds tool, which allows users to access real-time and archived climate model deterministic forecasts for sub-seasonal and seasonal timescales, from CFSv2 and NMME, by HUC4 sub-basin (gray outlines in the map), as well as the skill scores for the forecasts. (Source: http://hydro.rap.ucar.edu/s2s/)

Other activities to improve sub-seasonal forecasts and their use

SubX

The NOAA-funded Subseasonal Experiment (SubX) is a coordinated set of sub-seasonal prediction efforts and data archiving intended to explore the value of a multi-model ensemble for sub-seasonal forecasting (Pegion et al. 2019). This program was modeled after the NMME for seasonal forecasts (see next section). The SubX effort includes historical reforecasts (i.e., hindcasts) for 1999–2015 and real-time forecasts from seven modeling systems. Real-time forecast maps from the various models and from the multi-model ensemble are available on the SubX website.

Subseasonal Experiment—SubX



Link: http://cola.gmu.edu/subx/

Sub-Seasonal Forecast Rodeo

To promote the development of novel S2S forecasting methodologies, the Reclamation R&D program, in collaboration with NOAA and the California Department of Water Resources, held a Sub-Seasonal Forecast Rodeo from spring 2017 to spring 2018. Six teams of forecasters responded to an open public call and competed to produce the most skillful forecasts of temperature and precipitation across CONUS for weeks 3–4 (15–28 days out) and weeks 5–6 (29–42 days out). The forecasts were issued every two weeks for one year, with forecasts from the CFSv2 model used as a benchmark. Between one and three teams produced forecasts better than CFSv2, depending on the variable and lead time, with the most notable improvements seen in precipitation, for which CFSv2 showed almost no skill during the year-long contest period. (Note that in any given 1-year-period, CFSv2 and other forecast models and methods may significantly overperform or underperform relative to their longer-term skill, due to variability in the climate.) The methods of the winning teams will be made publicly available to potentially improve operational sub-seasonal forecasts. A second Sub-Seasonal Forecast Rodeo began in summer 2019.

Forecast Rodeo II

Link: https://www.drought.gov/drought/forecast-rodeo-ii-leaderboard

S2S workshops

The Western States Water Council and the California Department of Water Resources have co-sponsored a series of workshops to further dialogue among western states' water agencies and Reclamation, NOAA, and the research community on improving S2S precipitation forecasting to support water management decision making in the western U.S. The most recent workshop, in May 2018, included presentations on the operational and planning needs for seasonal climate forecasting in the Colorado River Basin, the mechanisms of cool-season precipitation in the Upper Basin, and climate forecasting challenges in the Upper Basin in the context of CBRFC streamflow forecasting.

Implications for the Colorado River Basin

While there is active research in all the areas of untapped sources of skill, it is hard to anticipate what the combined effect of many incremental improvements will be, including general improvements in weather and climate models and coupled (land-atmosphere-ocean) data assimilation, which are ongoing and will continue. The goal of much of this research is to push the boundaries of skillful and potentially useful probabilistic weather prediction into weeks 3 and 4, and this is where advances in skill are most likely to come, albeit from a relatively low baseline at present (e.g., Table 7.2).

Likewise, it is unclear whether any of the proposed pathways to improve skill discussed above will result in improved sub-seasonal forecasts specific to the Colorado River Basin. Based on the current literature, there is an indication that the Lower Basin may benefit from forecast improvements more than the Upper Basin. In particular, better representing combined effects of the MJO and QBO may improve precipitation forecast skill in the Lower Basin. The MJO is also known to modulate tropical cyclones in the eastern Pacific that occasionally cause heavy precipitation and flooding in the Lower Basin (Maloney and Hartmann 2000; Klotzbach 2014). It is plausible that the influence of the MJO on atmospheric rivers could, on occasion, affect the Upper Basin, but this has yet to be demonstrated. Improvement in treatment of the land surface and its influence on the atmosphere may lead to improvements in prediction of North American Monsoon precipitation that primarily affects the Lower Basin.

But even without significant improvements in overall forecast skill, there is still plenty of room to improve how the current skill of existing forecast systems is deployed by users of forecasts. The recent progress toward identifying "forecasts of opportunity" (Albers and Newman 2019; Mariotti et al. 2020) is a promising step toward more strategic deployment of sub-seasonal climate forecasts, i.e., consulting them in those locations, and during those seasons and specific times, when they are likely to have the most skill.

7.5 Seasonal climate forecasting

Overview and sources of predictability

The interest in predicting the climate on seasonal time scales to prepare for anomalous conditions is longstanding. The earliest published scientific effort in seasonal climate prediction was motivated by back-to-back failures of the Indian monsoon in 1876 and 1877 that caused a catastrophic drought (Blanford 1884). Blanford's investigation found that an abundant spring snowpack in the Himalayas was counterproductive for the Indian monsoon later that summer—an early insight into seasonal land surface feedbacks.

The effort to understand and predict the Indian Monsoon also fostered research by Sir Gilbert Walker in the early 1900s into the "Southern Oscillation," which is now understood as the El Niño-Southern Oscillation (ENSO) phenomenon (Chapter 2). A major breakthrough in the understanding of the functioning and influence of ENSO, and ultimately for seasonal climate forecasting, was the insight that ENSO was a coupled ocean-atmosphere phenomenon (Bjerknes 1966; 1969). It was later recognized that El Niño events resembled each other enough that it made sense to average them into a typical or canonical sequence (Rasmusson and Carpenter 1982). Such "compositing" became a key tool in unlocking the typical ENSO footprint of climate anomalies over North America (Ropelewski and Halpert 1987; 1989).

A general assumption in seasonal climate prediction is that the climate system displays preferred and recognizable patterns (footprints) that can be revealed through physical reasoning or statistical means. The search for analogues (Van den Dool 1994) is driven by the same notion that certain circulation patterns are more common than others, such as an enhanced southern winter storm track across the U.S. during El Niño. (CPC's empirical climate prediction methods that use the concepts of footprints and analogues is discussed in the next section.)

During the late 20th century, dynamical, fully physical climate models were increasingly run to simulate atmospheric conditions forced by (specified) anomalous sea surface temperature (SST) states to see whether the models could reproduce observed atmospheric behavior. As with short-term weather forecasts, the fast changing initial conditions in the atmosphere need to be captured to solve that portion of the forecast problem, while more slowly evolving conditions of the land and ocean were originally modeled as static boundary conditions (Gates et al. 1992).

Once it became clear that the modeled atmospheric behavior was realistic, the next step was to develop coupled ocean-atmosphere models that could be used to explore climate changes (i.e., GCMs; Chapter 11). These models were tested and refined by predicting ENSO events as well as seasonal climate anomalies (e.g., Becker, Van den Dool, and Zhang 2014; Bellenger et al. 2014; Weisheimer and Palmer 2014). These coupled Earth system models explicitly include evolving, rather than fixed, SST and land surface conditions. There are now more than a dozen coupled models that predict the state of ENSO in an operational manner, with highly variable, though overall positive, forecast skill (Barnston et al. 2012; 2017; Tippett et al. 2017). A key development in seasonal forecasting beyond ENSO was the discovery that global drought footprints of the swings of the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation (AMO) could be reproduced in coupled climate models (Schubert et al. 2009), though this discovery has yet to pay dividends for the Colorado River Basin (Chapter 2).

The current predictability and skill in seasonal forecasts still comes mainly from those sources identified during the long history of seasonal forecasting: the tendencies associated with key modes of ocean-atmosphere variability, primarily ENSO, other slowly varying processes such as land surface feedbacks, and robust long-term trends (e.g., warming temperatures).

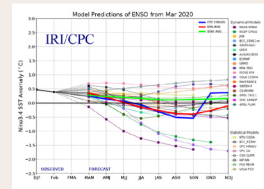
Operational seasonal climate forecasts from NOAA CPC

NOAA CPC and its predecessors have made a huge cumulative investment in developing and refining their seasonal forecasting methodology over several decades. While there are many other entities and individuals producing seasonal climate forecasts, ranging from the ECMWF to private consulting firms, the CPC forecasts are the most widely used in the U.S., across a broad spectrum of users, including in water resources, and serve as a benchmark for other efforts.

Starting in 1995, CPC settled on the current framework of seasonal (3-month) forecasts (called "outlooks") with multiple lead times out to 12.5 months. The two key ingredients supporting this framework were 1) the increasing community efforts to monitor and predict ENSO, as synthesized in a monthly updated [IRI ENSO "plume"](https://iri.columbia.edu) (Barnston et al. 2012); and 2) the development of the "Optimal Climate Normals" (OCN) methodology that takes advantage of longer-term climate variability and trends, whether linked to climate change or not. The CPC seasonal forecasts are released monthly, on the third Thursday of each month.

Figure 7.6 shows the January 2020 forecast for February–April 2020 (0.5 month lead time). These tercile forecasts are made in reference to the upper/middle/lower thirds of the 1981-2010 climatology (10 cases each), and the color shading shows tilts in the odds of one of the terciles in the climatological distribution (33%/33%/33%). For example, the darker brown shading for "B(elow)" in the precipitation outlook in Figure 7.6 means there is a 40–49% probability of seasonal precipitation for February–April being in the lower third of the historical distribution, compared to the

IRI/CPC ENSO Predictions Plume



Link: https://iri.columbia.edu/our-expertise/climate/forecasts/enso/current/?enso_tab=enso-sst_table

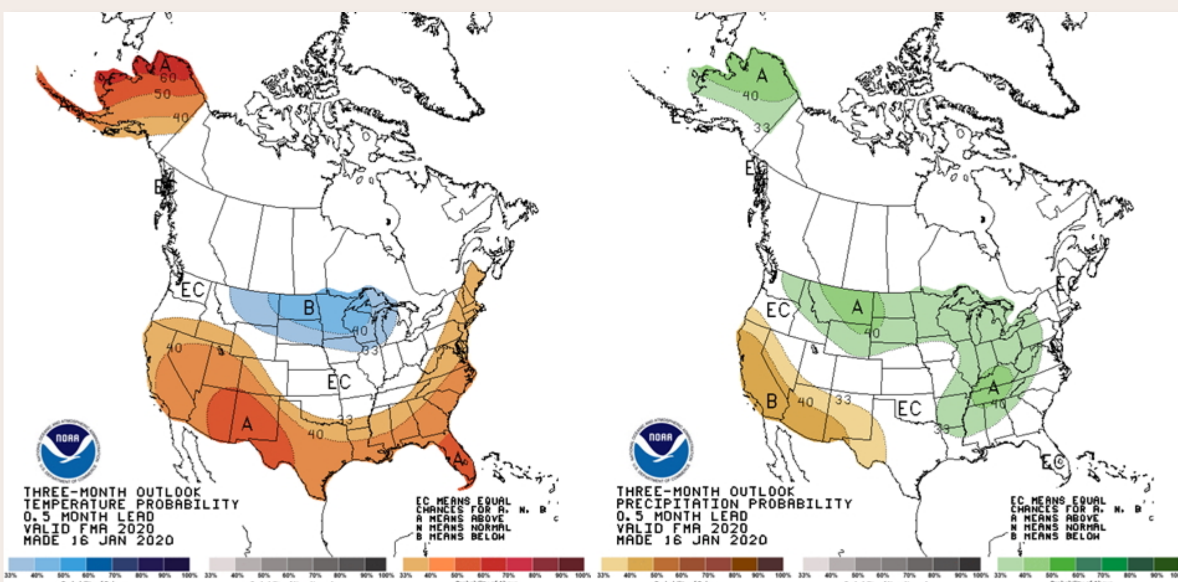


Figure 7.6

CPC seasonal outlooks for February–April 2020 for temperature (left) and precipitation (right), released on January 16, 2020. Darker shading shows tilts in the odds relative to the climatological (1981–2010) distribution of outcomes; see the text for further explanation. (Source: NOAA CPC; https://www.cpc.ncep.noaa.gov/products/predictions/long_range/)

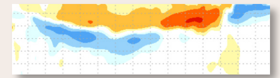
climatological probability of 33% for that outcome. If there is no appreciable tilt for any tercile, equal chances ("EC") are assigned.

CPC also produces a weekly ENSO status update, and an ENSO blog; both can be helpful in interpreting the physical mechanisms behind the seasonal forecasts.

Forecast tools

CPC uses a broad suite of forecast tools for seasonal forecasts, comprising both empirical (statistical) models and dynamical climate forecast models (Table 7.3). The two most important empirical tools are based on ENSO and Optimal Climate Normals (OCN), respectively. The other tools are Canonical Correlation Analysis (CCA), Ensemble CCA (ECCA), Constructed Analogues (CA), and Screening Multiple Linear Regression (SMLR). These empirical tools and their predecessors were the only quantitative guidance used in CPC forecasts prior to 2005; the dynamical tools were added to the suite of guidance around 2006. CPC provides a short introduction to all tools online.

ENSO: Recent Evolution, Current Status and Predictions



Link:
https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf

ENSO Blog

Link:
https://www.climate.gov/news-features/department/enso-blog

Table 7.3

Forecast tools used by NOAA CPC to inform their seasonal climate forecasts. Type: E = empirical; D = dynamical. The empirical tools that use multiple predictors (CCA, ECCA, CA, SMLR) are typically based on these four classes of predictors: 200mb global velocity potential (upper air flow information), global sea surface temperatures (SST), sea-level pressure north of 40°N, and U.S. soil moisture. (Source: NOAA CPC; https://www.cpc.ncep.noaa.gov/products/predictions/long_range/tools.php)

Forecast Tool	Type	Usual importance to forecasts	Contribution to forecasts	Comments	Reference
ENSO Composites	E	Higher	Typical climate "footprint" of the current or forecasted ENSO state	The mainstay of CPC seasonal forecasts	Higgins, Kim, and Unger (2004)
Optimal Climate Normals (OCN)	E	Higher	Recent (15-year) trends in temperature and precipitation, if different from longer-term (30-year) normal	During clear-cut El Niño or La Niña events, ENSO composites include OCN information in a single tool	Huang, Van den Dool, and Barnston (1996); Van den Dool (2007)
CFSv2 model	D	Higher	Physically based prediction of future climate conditions	Also included in NMME	Saha et al. (2014)

Forecast Tool	Type	Usual importance to forecasts	Contribution to forecasts	Comments	Reference
NMME model ensemble	D	Higher	Physically based prediction of future climate; ensemble shows uncertainty due to model structure; ensemble mean more skillful than any one model	Ensemble of 7 models: CFSv2 (NOAA); CanCM4i and GEM-NEMO (Canada); FLOR and CM2.1 (NOAA GFDL); CCSM4 (NCAR); GEOS S2S (NASA)	Kirtman et al. (2014)
Canonical Correlation Analysis (CCA)	E	Lower	Influence of multiple predictors of future climate conditions as captured in linear relationships		Barnston (1994)
Ensemble CCA (ECCA)	E	Lower	Same as above	Only used for temperature	Mo (2003)
Constructed Analogues (CA)	E	Lower	Same as above	Most useful when analogues are based on soil moisture	Van den Dool (1994; 2003)
Screening Multiple Linear Regression (SMLR)	E	Lower	Same as above	Refined version of MLR tools used by early forecasters	O'Lenic et al. (2008)

As mentioned before, ENSO information and OCN have been the primary tools since the 1990s; as new forecast tools were added, each needed to have a skill assessment using reforecasts. The dynamical coupled forecast models (CFSv2 and the NMME ensemble) were evaluated even more critically; they had to reproduce empirical ENSO results before being included as guidance. When the consensus among the different tools is strong, that information is used to tweak the odds in the forecasts (e.g., moving from a 40% to 50% probability for the wettest tercile). Particularly strong ENSO signals, or regional trends, like the warming trend in the western U.S., will tend to yield high "tilts" in the odds.

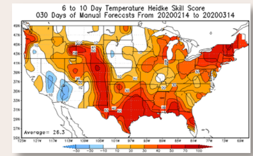
Operational skill of CPC seasonal forecasts

CPC has archived all 0.5-month lead forecasts since 1995 and their national skill scores are online. The long-term (1995–2019) average Heidke skill score (HSS) for temperature has been 14, while the average HSS for precipitation has been 4, where 100 is perfect skill and 0 is no skill. As with sub-seasonal forecasts, seasonal forecasts in general are more skillful for temperature than for precipitation. This disparity has been seen across the globe by different forecasting groups; e.g., Weisheimer and Palmer (2014)

(As described earlier in this chapter, Heidke skill is based on “hits”; if 20 of 60 seasonal forecasts “hit” for the correct tercile—as would be expected by chance alone—the skill score is 0; if all 60 are correct, the skill score is 100, and if none of them are correct, the score is -50.)

The skill of the CPC seasonal forecasts has been highly variable over time, with several periods during which the temperature forecasts had an HSS over 50 and precipitation forecasts had an HSS over 30. Conversely, there have been many periods of negative skill (<0), especially for precipitation. Most of the variation appears to correspond to the strength of ENSO events; when moderate to strong El Niño and La Niña events emerge, the ENSO forecast models generally perform better (Barnston et al. 2012), and the footprints of ENSO impacts on the western U.S. are more predictable. Livezey and Timofeyeva (2008) showed that most of the nationwide skill of the first decade (1995–2005) of seasonal CPC forecasts was due to the “Super El Niño” of 1997–98, the long-lived La Niña of 1998–2001, and other strong ENSO events. During periods when ENSO-neutral conditions prevail, seasonal forecasts in the U.S. are generally less skillful.

CPC Verification Summary



Link: https://www.cpc.ncep.noaa.gov/products/verification/summary/

Regional skill in the Colorado River Basin

Skill of operational seasonal outlooks for the Colorado River Basin

The Upper Basin was identified early on as an area of relatively weak to non-existent ENSO signals in precipitation, compared to the ends of the ENSO dipole: El Niño wetness in the Southwest and La Niña wetness in the Northwest (Redmond and Koch 1991; see Chapter 2). Thus, CPC’s early ENSO-related forecasts often left the Upper Basin blank, or EC, except for the 1997–98 super El Niño. Wolter et al. (1999) uncovered more nuance in the ENSO signal, finding distinct seasonality in the Upper Basin’s response to ENSO.

Maps of skill for the CPC seasonal precipitation outlooks issued from 1995–2019 are shown in Figure 7.7, for the four 3-month seasons of the water year. For the Upper Basin, skill has been highest in late winter (JFM) and spring (AMJ), hitting Heidke skill scores of up to 20 along the southern periphery of the Upper Basin. In contrast, late summer and fall forecasts have shown no overall skill across the 1995–2019 period. For the Lower Basin, skill has been highest in late winter (JFM), with skill scores up to 40 in western New Mexico and at least 30 in nearly all of the Lower Basin. This seasonal peak in skill mainly reflects the footprint of ENSO events being expressed most strongly in late winter. There has been less skill or no skill in the other three seasons, except for northwestern Arizona in spring.

During the most recent decade (2010–2019) skill during late winter (JFM) over the Lower Basin has been higher than during the full period as shown in Figure 7.7. Also, during 2010–2019, skill during spring (AMJ) has been much higher in both the Upper and Lower Basins than during the full period. This recent performance may reflect improvements in the forecast system and thus might be expected to continue. Figure 7.8 shows maps of skill for the CPC seasonal temperature outlooks issued from 1995–2019, for the four, 3-month seasons of the water year. For both the Upper Basin and Lower Basin, positive skill is seen in all four seasons, with somewhat higher skill for the Lower Basin. The HSS is over 50 for large portions of the Lower Basin in all four seasons, and portions of the Upper Basin in spring and summer. Much of the skill in temperature outlooks in the western U.S. is due to the consistent increasing trends in seasonal and annual temperature, as captured in the OCN tool.

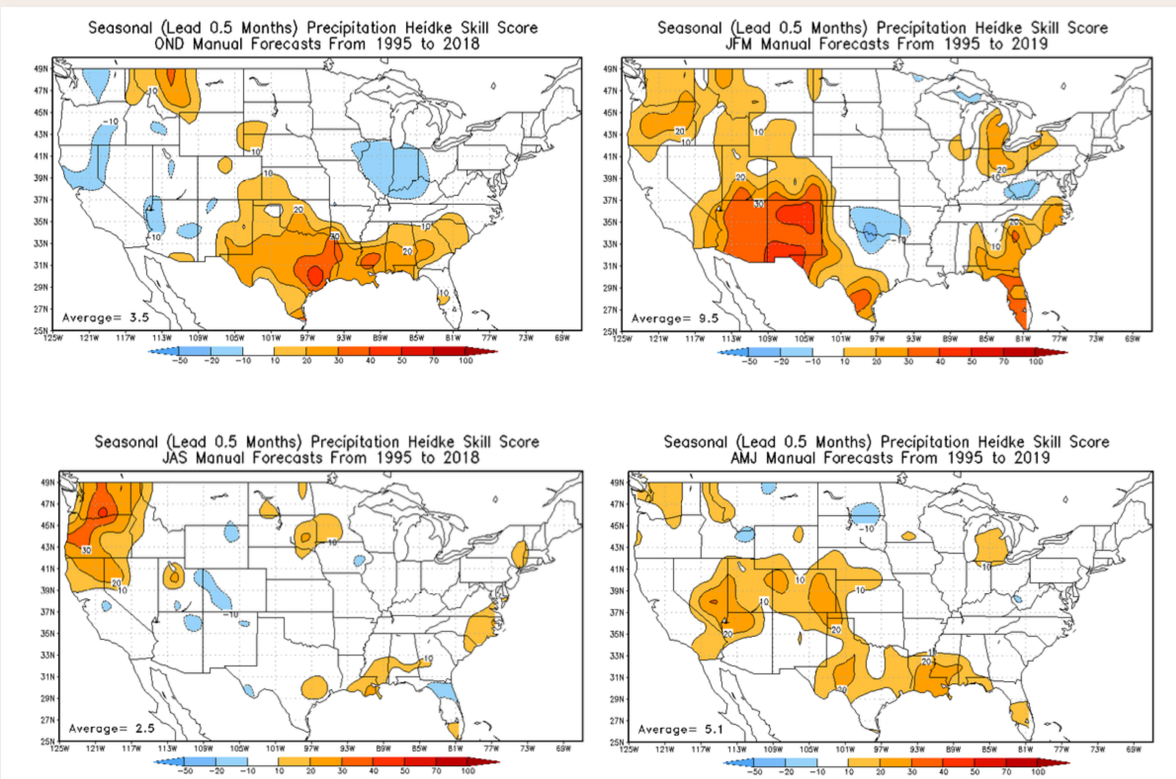


Figure 7.7

Maps of CPC seasonal precipitation forecast skill (Heidke Skill Score; HSS) from 1995–2019, using seasons that correspond to quarters of the water year: October-December (upper left); January-March (upper right); April-June (lower right); and July-September (lower left). Positive skill (orange colors) in the Upper Basin is limited to winter-spring (JFM and AMJ; (HSS=10-20). In the Lower Basin, positive skill is seen mainly in winter (JFM) and is higher (30–40) than in the Upper Basin. (Source: NOAA CPC; https://www.cpc.ncep.noaa.gov/products/verification/summary/)

Skill of NMME model forecasts for the Colorado River Basin

As described above, the NMME dynamical model ensemble is one of the tools now used by CPC forecasters to inform operational seasonal forecasts for the Upper and Lower Basin. In Table 7.4, the skill scores for NMME forecasts for season 1 (1–90 days out) are shown for the Upper and Lower Basin. As with the sub-seasonal model forecasts from NMME and CFSv2, temperature is forecasted more skillfully than precipitation, and the Lower Basin seasonal climate is more skillfully forecasted than in the Upper Basin.

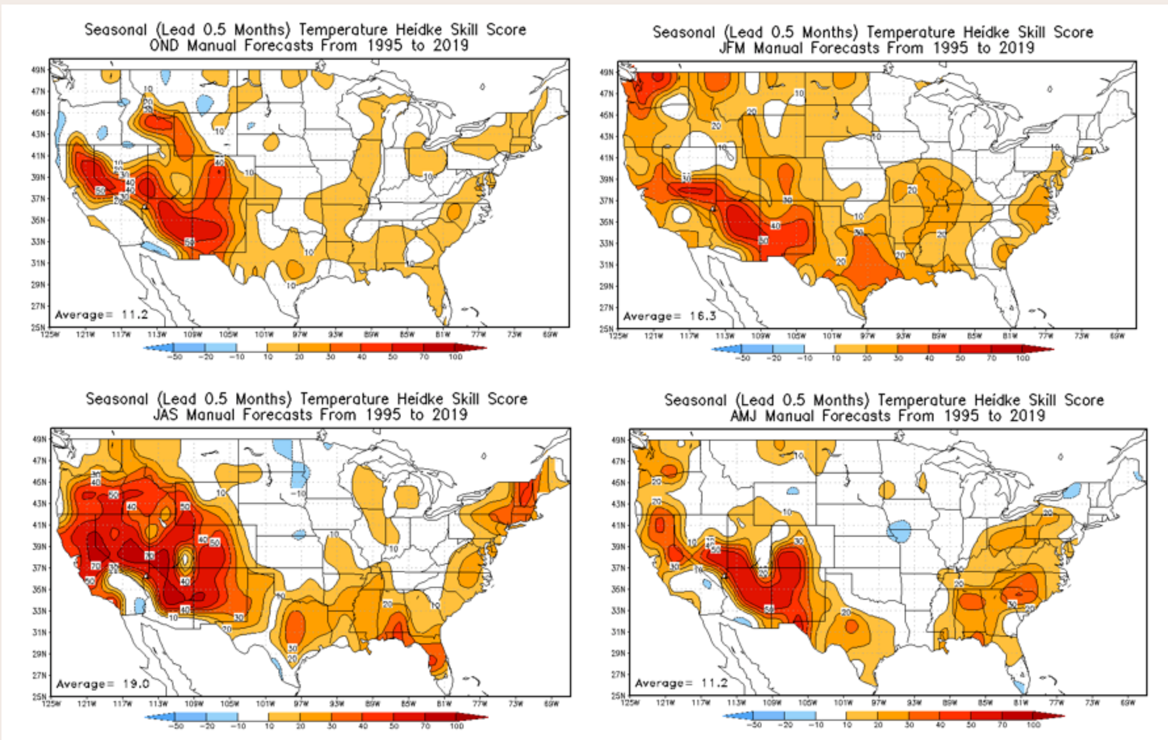


Figure 7.8

Maps of CPC seasonal temperature forecast skill (Heidke Skill Score; HSS) from 1995–2019, using seasons that correspond to quarters of the water year: October-December (upper left); January-March (upper right); April-June (lower right); and July-September (lower left). Positive skill (orange and red colors) is seen in both the Upper Basin and Lower Basin in all seasons, with the highest overall skill in late summer (July-September). (Source: NOAA CPC; https://www.cpc.ncep.noaa.gov/products/verification/summary/)

Table 7.4

Skill (Anomaly Correlation; AC) for Season 1 (1–90 days out) forecasts from the NMME forecast ensemble (7 models, including CFSv2) across the calendar year (annual) and for the climatological seasons, based on reforecasts for the 1981–2010 period. The skill scores for the eight HUC4 sub-basins each in the Upper Basin and Lower Basin were averaged to the basin-wide scores shown here. (Data: S2S Outlooks for Watersheds; http://hydro.rap.ucar.edu/s2s/)

Skill (AC) for Season 1 forecasts, NMME ensemble						
Variable	Basin	Annual	DJF	MAM	JJA	SON
Precipitation	Upper Basin	0.19	0.19	0.29	0.11	0.15
	Lower Basin	0.27	0.41	0.28	0.09	0.20
Temperature	Upper Basin	0.19	0.12	0.25	0.24	0.20
	Lower Basin	0.31	0.28	0.31	0.30	0.36

As with the operational CPC forecasts—which incorporate the NMME along with other guidance (Figure 7.7)—the NMME results in Table 7.4 indicate that predictability in seasonal precipitation is greater in the winter and spring than in the summer and fall, with a spring peak in the Upper Basin and winter peak in the Lower Basin—which is helpful, since the former two seasons best correspond to snowpack accumulation and water-year runoff. However, even in winter and spring, seasonal forecast skill is still relatively low.

Activities to improve seasonal forecast skill in the Colorado River Basin

SWcasts—precipitation outlooks for the interior Southwest

Since ENSO only explains a fraction of seasonal climate variability in the interior Southwest (Utah, Colorado, New Mexico, Arizona), and since SNOTEL information was not incorporated into climate divisions (nor CPC forecasts), Wolter (2002) embarked on an effort in the late 1990s to create statistical seasonal forecasts (SWCasts) that increased the pool of predictors beyond ENSO, and improve the temperature and precipitation predictands by including SNOTEL data (Chapter 5). To create forecast zones within the 4-state region, SNOTEL and weather stations were grouped into core regions using statistical analyses to select the most similar ones, with one set of 6–10 regions each for four meteorological seasons.

For potential predictors, previously established teleconnection indices (e.g., ENSO indices, North Atlantic Oscillation, etc.), as well as tropical Pacific or

Indian Ocean, and Gulf of Mexico SSTs were considered. Some predictors had been discovered a century ago, such as key sea-level pressure regions in the Pacific and Indian oceans. Inspired by Knaff and Landsea (1997) and similar to O'Lenic et al. (2008), SWcasts employs Screening Multiple Linear Regression (SMLR) as a statistical forecast tool. Over the following 16 years of forecasts, the balance of "hits" versus "misses" was sufficiently positive to translate into positive skill scores. During this period, forecast skill for the Upper Basin (in CO and UT) was worst during fall and best during winter and summer. While there were pockets of exceptional skill during winter (southeast CO) and summer (central NM and northern UT), overall skill scores were not significantly higher than for the CPC operational seasonal forecasts (Figure 7.7).

While the production and issuance of SWcasts ended in 2018, a renewed effort at regional statistical forecasts could capitalize on two decades of additional training data for both predictors and predictands, and improved forecast schemes.

Seasonal forecasts of SWE using GCMs

Kapnick et al. (2018) drew widespread attention with their claim of skillful prediction of regional snowpack (SWE) conditions up to 8 months in advance using a suite of coupled climate models (i.e., GCMs) developed by NOAA GFDL to generate hindcasts for the 1981–2015 period. While they show skill over the western U.S. overall (average correlation of 0.48) and in many sub-regions, the lowest skill (correlation of about 0.30) was found in their Colorado Rockies sub-region, which comprises western Colorado and is the source of about 70% of Upper Basin streamflow. So the relevance of their findings for the Colorado River Basin is more limited than for other regions. Overall, their spatial patterns of skill in predicting snowpack, temperature, precipitation, and storm tracks strongly suggest that they have largely rediscovered the well-known ENSO influence on western U.S. hydroclimate, rather than a truly novel capability of GCMs.

Year 2 predictability during La Niña events

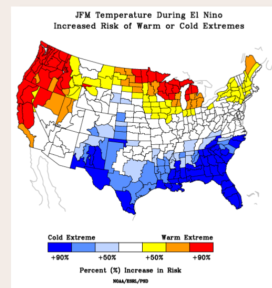
Wolter and Timlin (2011) diagnosed that La Niña events have a much higher propensity for multi-year extension than El Niño events. More importantly, there is a strong tendency for a second-year La Niña to be significantly drier in the Upper Colorado River Basin than the first year. Two of the most severe multi-year droughts since 1950 (mid-1950s and early 2000s) were anchored by such long-lived La Niñas. This tendency was seen again in the two-year La Niña events of 2011–2013 and 2016–2018. Okumura, DiNezio, and Deser (2017) independently confirmed this observation of a drier second year during La Niña. However, this only covers a subset of years, and two-year La Niñas are not guaranteed once a La Niña event sets in.

Implications for the Colorado River Basin

The fundamental challenge inhibiting skillful seasonal climate forecasting in the Upper Basin is the same as that at the start of CPC's operational forecasts almost 25 years ago: Seasonal forecasting skill across the western U.S.—and in most of the world—is largely predicated on ENSO signals, especially for precipitation, but those ENSO signals are overall weak or cancel out on the scale of the entire Upper Basin, and across the fall–winter-spring seasons when most of the water supply is generated. However, there appears to be enough skill for there to be a benefit using climate forecast model output to slightly tilt or weight the ensemble of CBRFC seasonal streamflow forecasts for the Upper Basin, as was done in work by Baker (2019) (Chapter 8.) For the Lower Basin, seasonal climate forecast skill is generally higher than in the Upper Basin, but still much lower than for weather forecasts.

As with sub-seasonal forecasts, perhaps the shortest pathway to "improvement" is for forecast users to judiciously and selectively use seasonal climate forecasts, consulting them only during those seasons, and during those ENSO states (i.e., moderate to strong El Niño and La Niña events) in which more predictability and skill is seen (Figure 7.7 and Table 7.4). A potentially helpful information source in this regard is the NOAA PSD ENSO climate risk tool that shows which climate divisions have significantly increased or decreased risk of seasonal wet and dry extremes (>80th percentile) during moderate to strong ENSO events. During some strong ENSO events, the CBRFC has used ENSO information to adjust streamflow forecasts in the Lower Basin through trace-weighting (see Chapter 8).

Risk of Seasonal Climate Extremes in the U.S. Related to ENSO



Link: https://www.esrl.noaa.gov/psd/enso/climaterisks/

7.6 Challenges and opportunities

While there are still many challenges being tackled by the weather forecasting research community to obtain greater understanding and predictive skill, the level of performance and skill is already relatively high, and progressing well. Thus, from the perspective of water supply forecasting and management, the most pressing challenges and most compelling opportunities are at sub-seasonal and seasonal timescales. In the Colorado River Basin, and the Upper Basin especially, the limited skill of sub-seasonal and seasonal forecasts for precipitation and even temperature constrains usability.

There is no single pathway toward improvement in the skill and usability of climate forecasts for the basin. There are, though, broad families of ongoing activities that in combination can lead to such improvement. It is probably neither feasible nor desirable to coordinate all of these activities, since many of them connect with efforts at broader scales; what is important is that researchers, funders, and stakeholders are at least made aware of the suite of activities, for example, through the Western States Water Council-California Department of Water Resources workshop series. And, given the history and current state of climate forecasting, no one should expect easy wins producing large gains in skill or usability; incremental improvement is the likeliest outcome of any effort.

Challenge

Limitations in our understanding of the connections between atmospheric and oceanic circulation patterns and processes, and Colorado River Basin precipitation variability in space and time, constrain the skill of climate forecast models in forecasting conditions for the basin.

Opportunities

- Support further research into these climate system dynamics to identify key patterns and variables.
- Support further research into better representing those key patterns and variables in dynamical climate forecast models and statistical forecast tools.

Challenge

The CBRFC and other streamflow forecasting units may not be able to capitalize on the skill that does exist in sub-seasonal and seasonal climate forecasts for the basin.

Opportunities

- Support ongoing CBRFC efforts to pilot the inclusion of sub-seasonal and seasonal forecasts in their forecast system (see Chapter 8).
- Support further research into post-processing of CBRFC forecasts to generate climate-forecast-informed, use-specific streamflow forecasts (see Chapter 8).

Challenge

The limited skill and probabilistic nature of climate forecasts may not mesh well with decision frameworks so water managers are unable to extract value from the forecast information.

Opportunities

- Continue to support engagement between water managers and CPC and other climate forecasters to facilitate shared understanding of decision needs and forecast capabilities.
- Study decision making by users and sectors that make better use of climate forecasts (e.g., crop futures traders), to assess transferability of tools and practices.
- Develop decision support tools that bridge climate forecasts to the water resource decision space.

Challenge

The skill of climate forecasts is highly variable over both space and time, complicating the consistent use of forecasts.

Opportunities

- Selectively consult forecasts during those seasons when they have shown the most skill for the basin.
- Support research to identify "forecasts of opportunity" specific to the basin, i.e., conditions of the ocean, atmosphere, and land surface during which forecasts are more likely to have skill and impact.

References

Abatzoglou, John T. 2013. "Development of Gridded Surface Meteorological Data for Ecological Applications and Modelling." *International Journal of Climatology* 33 (1): 121–31. https://doi.org/10.1002/joc.3413.

———. 2019. "Climatology Lab." Gridmet. 2019. http://www.climatologylab.org/gridmet.html.

Abatzoglou, John T., and Timothy J. Brown. 2012. "A Comparison of Statistical Downscaling Methods Suited for Wildfire Applications." International Journal of Climatology 32 (5): 772–80. https://doi.org/10.1002/joc.2312.

Adam, Jennifer C., and Dennis P. Lettenmaier. 2003. "Adjustment of Global Gridded Precipitation for Systematic Bias." Journal of Geophysical Research: Atmospheres 108 (D9): n/a-n/a. https://doi.org/10.1029/2002JD002499.

Adams, David K., and Andrew C. Comrie. 1997. "The North American Monsoon." Bulletin of the American Meteorological Society, 2197–2213. https://doi.org/10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2.

Adams, Thomas E., III, and Randel Dymond. 2018. "Evaluation and Benchmarking of Operational Short-Range Ensemble Mean and Median Streamflow Forecasts for the Ohio River Basin." Journal of Hydrometeorology 19 (10): 1689–1706. https://doi.org/10.1175/JHM-D-18-0102.1.

Albano, Christine M., Michael D. Dettinger, Maureen I. McCarthy, Kevin D. Schaller, Toby L. Welborn, and Dale A. Cox. 2016. "Application of an Extreme Winter Storm Scenario to Identify Vulnerabilities, Mitigation Options, and Science Needs in the Sierra Nevada Mountains, USA." Natural Hazards 80 (2): 879–900. https://doi.org/10.1007/s11069-015-2003-4.

Albers, John R., and Matthew Newman. 2019. "A Priori Identification of Skillful Extratropical Subseasonal Forecasts." Geophysical Research Letters 46 (21): 12527–36. https://doi.org/10.1029/2019GL085270.

Alder, Jay R., and Steven W. Hostetler. 2019. "The Dependence of Hydroclimate Projections in Snow-Dominated Regions of the Western United States on the Choice of Statistically Downscaled Climate Data." Water Resources Research 55 (3): 2279–2300. https://doi.org/10.1029/2018WR023458.

Alder, Jay R., and Steven W. Hostetler. 2015. "Web Based Visualization of Large Climate Data Sets." Environmental Modelling & Software 68 (June): 175–80. https://doi.org/10.1016/j.envsoft.2015.02.016.

Allaby, Michael. 2008. A Dictionary of Earth Sciences. Oxford University Press. https://www.oxfordreference.com/view/10.1093/acref/9780199211944.001.0001/acref-9780199211944.

Allen, Richard G., L. S. Pereira, Dirk Raes, and Martin Smith. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. Rome: Food and Agriculture Organization of the United Nations.

Allen, Richard G., Masahiro Tasumi, and Ricardo Trezza. 2007. "Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Model." Journal of Irrigation and Drainage Engineering 133 (4): 380–94. https://doi.org/10.1061/(ASCE)0733-9437(2007)133:4(380).

Alley, William M., and Leonard F. Konikow. 2015. "Bringing GRACE Down to Earth." Groundwater 53 (6): castle. https://doi.org/10.1111/gwat.12379.

Amatya, Devendra M., Suat Irmak, Prasanna Gowda, Ge Sun, Jami E. Nettles, and Kyle R. Douglas-Mankin. 2016. "Ecosystem Evapotranspiration: Challenges in Measurements, Estimates, and Modeling." Transactions of the ASABE 59 (2): 555–60. https://doi.org/10.13031/trans.59.11808.

Anderson, Brian Trail. 2011. "Spatial Distribution and Evolution of a Seasonal Snowpack in Complex Terrain: An Evaluation of the SNODAS Modeling Product." PhD Dissertation, Boise State University.

Anderson, Eric A. 1973. "National Weather Service River Forecast System-Snow Accumulation and Ablation Model." NWS HYDRO-17. NOAA Technical Memorandum.

Anderson, M. G., and T. P. Burt. 1985. Hydrological Forecasting. https://www.osti.gov/biblio/6271151.

Anderson, Martha C., Christopher Hain, Brian Wardlow, Agustin Pimstein, John R. Mecikalski, and William P. Kustas. 2011. "Evaluation of Drought Indices Based on Thermal Remote Sensing of Evapotranspiration over the Continental United States." Journal of Climate 24 (8): 2025–44. https://doi.org/10.1175/2010JCLI3812.1.

Anderson, Martha C., J. M. Norman, G. R. Diak, William P. Kustas, and John R. Mecikalski. 1997. "A Two-Source Time-Integrated Model for Estimating Surface Fluxes Using Thermal Infrared Remote Sensing." Remote Sensing of Environment 60 (2): 195–216. https://doi.org/10.1016/S0034-4257(96)00215-5.

Anderson, Richard M., Victor I. Koren, and Seann M. Reed. 2006. "Using SSURGO Data to Improve Sacramento Model a Priori Parameter Estimates." Journal of Hydrology 320 (1–2): 103–16. https://doi.org/10.1016/j.jhydrol.2005.07.020.

Anderson, SallyRose, Glenn Tootle, and Henri Grissino-Mayer. 2012. "Reconstructions of Soil Moisture for the Upper Colorado River Basin Using Tree-Ring Chronologies." JAWRA Journal of the American Water Resources Association 48 (4): 849–58. https://doi.org/10.1111/j.1752-1688.2012.00651.x.

Andreadis, Konstantinos M., Elizabeth A. Clark, Andrew W. Wood, Alan F. Hamlet, and Dennis P. Lettenmaier. 2005. "Twentieth-Century Drought in the Conterminous United States." Journal of Hydrometeorology 6 (6): 985–1001. https://doi.org/10.1175/JHM450.1.

Ault, Toby R., Julia E. Cole, Jonathan T. Overpeck, Gregory T. Pederson, and David M. Meko. 2014. "Assessing the Risk of Persistent Drought Using Climate Model Simulations and Paleoclimate Data." Journal of Climate 27 (20): 7529–49. https://doi.org/10.1175/JCLI-D-12-00282.1.

Ault, Toby R., Julia E. Cole, Jonathan T. Overpeck, Gregory T. Pederson, Scott St. George, Bette Otto-Bliesner, Connie A. Woodhouse, and Clara Deser. 2013. "The Continuum of Hydroclimate Variability in Western North America during the Last Millennium." Journal of Climate 26 (16): 5863–78. https://doi.org/10.1175/JCLI-D-11-00732.1.

Ault, Toby R., Justin S. Mankin, Benjamin I. Cook, and Jason E. Smerdon. 2016. "Relative Impacts of Mitigation, Temperature, and Precipitation on 21st-Century Megadrought Risk in the American Southwest." Science Advances 2 (10): e1600873. https://doi.org/10.1126/sciadv.1600873.

Ault, Toby R., and Scott St. George. 2018. "Unraveling the Mysteries of Megadrought." Physics Today 71 (8): 44–50. https://doi.org/10.1063/PT.3.3997.

Baker, Sarah A. 2019. "Development of Sub-Seasonal to Seasonal Watershed-Scale Hydroclimate Forecast Techniques to Support Water Management." Dissertation, Boulder, CO: University of Colorado. https://search.proquest.com/openview/86480abe8a4f1b7c3f0bccc9bf5142ac/1?pq-origsite=gscholar&cbl=18750&diss=y.

Baker, Sarah A., Andrew W. Wood, and Balaji Rajagopalan. 2019. "Developing Subseasonal to Seasonal Climate Forecast Products for Hydrology and Water Management." JAWRA Journal of the American Water Resources Association 55 (4): 1024–37. https://doi.org/10.1111/1752-1688.12746.

Bardsley, Tim, Andrew W. Wood, Michael T. Hobbins, T. Kirkham, L. Briefer, J. Niermeyer, and S. Burian. 2013. "Planning for an Uncertain Future: Climate Change Sensitivity Assessment toward Adaptation Planning for Public Water Supply." Earth Interactions 17: 1–26.

Barnett, Tim P., and David W. Pierce. 2009. "Sustainable Water Deliveries from the Colorado River in a Changing Climate." Proceedings of the National Academy of Sciences 106 (18): 7334–38. https://doi.org/10.1073/pnas.0812762106.

Barnett, Tim P., David W. Pierce, Hugo G. Hidalgo, Celine Bonfils, Benjamin D. Santer, Tapash Das, Govindasamy Bala, et al. 2008. "Human-Induced Changes in the Hydrology of the Western United States." Science 319 (5866): 1080–83. https://doi.org/10.1126/science.1152538.

Barnhart, Theodore B., Noah P. Molotch, Ben Livneh, Adrian A. Harpold, John F. Knowles, and Dominik Schneider. 2016. "Snowmelt Rate Dictates Streamflow." Geophysical Research Letters 43 (15): 8006–16. https://doi.org/10.1002/2016GL069690.

Barnston, Anthony G. 1994. "Linear Statistical Short-Term Climate Predictive Skill in the Northern Hemisphere." Journal of Climate 7: 1513–64. https://doi.org/10.1175/1520-0442(1994)007<1513:LSSTCP>2.0.CO;2.

Barnston, Anthony G., Michael K. Tippett, Michelle L. L'Heureux, Shuhua Li, and David G. DeWitt. 2012. "Skill of Real-Time Seasonal ENSO Model Predictions during 2002–11: Is Our Capability Increasing?" Bulletin of the American Meteorological Society 93 (5): 631–51. https://doi.org/10.1175/BAMS-D-11-00111.1.

Barnston, Anthony G., Michael K. Tippett, Meghana Ranganathan, and Michelle L. L'Heureux. 2017. "Deterministic Skill of ENSO Predictions from the North American Multimodel Ensemble." Climate Dynamics, March. https://doi.org/10.1007/s00382-017-3603-3.

Barrett, Andrew P. 2003. "National Operational Hydrologic Remote Sensing Center SNOw Data Assimilation System (SNODAS) Products at NSIDC." 11. Special Report. National Snow and Ice Data Center (NSIDC).

Barros, Ana Paula, and Dennis P. Lettenmaier. 1994. "Incorporation of an Evaporative Cooling Scheme into a Dynamic Model of Orographic Precipitation." Monthly Weather Review 122: 2777–83.

Barry, R.G., and R.J. Chorley. 2010. Atmosphere, Weather and Climate. Routledge. https://books.google.com/books?id=heM0uAAACAAJ.

Barsugli, Joseph J., Christopher J. Anderson, Joel B. Smith, and Jason M. Vogel. 2009. "Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change." Water Utility Climate Alliance.

Barsugli, Joseph J., and Ben Livneh. 2018. "A Workshop on Understanding the Causes of the Historical Changes in Flow of the Colorado River." Workshop Report. Boulder, CO: NOAA Earth Systems Research Laboratory.

Battaglin, William, Lauren Hay, and Steven L. Markstrom. 2011. "Simulating the Potential Effects of Climate Change in Two Colorado Basins and at Two Colorado Ski Areas." Earth Interactions 15 (22): 1–23. https://doi.org/10.1175/2011EI373.1.

Bauer, Peter, Alan Thorpe, and Gilbert Brunet. 2015. "The Quiet Revolution of Numerical Weather Prediction." Nature 525 (7567): 47–55. https://doi.org/10.1038/nature14956.

Becker, Emily, Huug M. Van den Dool, and Qin Zhang. 2014. "Predictability and Forecast Skill in NMME." Journal of Climate 27 (15): 5891–5906. https://doi.org/10.1175/JCLI-D-13-00597.1.

Beckers, J. V. L., A. H. Weerts, E. Tijdeman, and E. Welles. 2016. "ENSO-Conditioned Weather Resampling Method for Seasonal Ensemble Streamflow Prediction." Hydrol. Earth Syst. Sci. 20 (8): 3277–87. https://doi.org/10.5194/hess-20-3277-2016.

Behnke, Ruben, S. Vavrus, A. Allstadt, T. Albright, W. E. Thogmartin, and V. C. Radeloff. 2016. "Evaluation of Downscaled, Gridded Climate Data for the Conterminous United States." Ecological Applications 26 (5): 1338–51. https://doi.org/10.1002/15-1061.

Behnke, Ruben, Steve Vavrus, Andrew Allstadt, Thomas Albright, W. E. Thogmartin, and V. C. Radeloff. 2016. "Evaluation of Downscaled, Gridded Climate Data for the Conterminous United States." Ecological Applications 26 (5): 1338–51. https://doi.org/10.1002/15-1061.

Bellenger, H., E. Guilyardi, J. Leloup, M. Lengaigne, and J. Vialard. 2014. “ENSO Representation in Climate Models: From CMIP3 to CMIP5.” Climate Dynamics 42 (7–8): 1999–2018. https://doi.org/10.1007/s00382-013-1783-z.

Bender, Jens, Thomas Wahl, and Jürgen Jensen. 2014. “Multivariate Design in the Presence of Non-Stationarity.” Journal of Hydrology 514 (June): 123–30. https://doi.org/10.1016/j.jhydrol.2014.04.017.

Bender, Stacie, Paul Miller, Brent Bernard, and John Lhotak. 2014. “Use of Snow Data from Remote Sensing in Operational Streamflow Prediction.” In , 11.

Bergeron, Jean M., Mélanie Trudel, and Robert Leconte. 2016. “Combined Assimilation of Streamflow and Snow Water Equivalent for Mid-Term Ensemble Streamflow Forecasts in Snow-Dominated Regions.” Hydrology and Earth System Sciences 20 (10): 4375–89. https://doi.org/10.5194/hess-20-4375-2016.

Berghuijs, W. R., R. A. Woods, and M. Hrachowitz. 2014. “A Precipitation Shift from Snow towards Rain Leads to a Decrease in Streamflow.” Nature Climate Change 4 (7): 583–86. https://doi.org/10.1038/nclimate2246.

Best, M. J., G. Abramowitz, H. R. Johnson, A. J. Pitman, G. Balsamo, A. Boone, M. Cuntz, et al. 2015. “The Plumbing of Land Surface Models: Benchmarking Model Performance.” Journal of Hydrometeorology 16 (3): 1425–42. https://doi.org/10.1175/JHM-D-14-0158.1.

Beven, Keith J. 2002. “Towards an Alternative Blueprint for a Physically Based Digitally Simulated Hydrologic Response Modelling System.” Hydrological Processes 16 (2): 189–206. https://doi.org/10.1002/hyp.343.

———. 2012. Rainfall-Runoff Modelling: The Primer. 2nd ed. Wiley-Blackwell.

Beven, Keith J., and Hannah L. Cloke. 2012. “Comment on ‘Hyperresolution Global Land Surface Modeling: Meeting a Grand Challenge for Monitoring Earth’s Terrestrial Water’ by Eric F. Wood et Al.” Water Resources Research 48 (1). https://doi.org/10.1029/2011WR010982.

Biddle, Suzanne Hardy. 2001. “Optimizing the TVA Reservoir System Using Riverware.” In Bridging the Gap, 1–6. Proceedings. https://doi.org/10.1061/40569(2001)149.

Biondi, Franco, Alexander Gershunov, and Daniel R. Cayan. 2001. “North Pacific Decadal Climate Variability since 1661.” Journal of Climate 14 (1): 5–10. https://doi.org/10.1175/1520-0442(2001)014<0005:NPDCVS>2.0.CO;2.

Bjerknes, J. 1966. “A Possible Response of the Atmospheric Hadley Circulation to Equatorial Anomalies of Ocean Temperature.” Tellus 18 (4): 820–29. https://doi.org/10.1111/j.2153-3490.1966.tb00303.x.

———. 1969. “Atmospheric Teleconnections from the Equatorial Pacific.” Monthly Weather Review 97: 163–72. https://doi.org/10.1175/1520-0493(1969)097<0163:ATFTEP>2.3.CO;2.

Blanford, H. F. 1884. “On the Connexion of the Himalaya Snowfall with Dry Winds and Seasons of Drought in India.” Proceedings of the Royal Society of London 37: 21.

Blankenship, Clay B., Jonathan L. Case, William L. Crosson, and Bradley T. Zavodsky. 2018. “Correction of Forcing-Related Spatial Artifacts in a Land Surface Model by Satellite Soil Moisture Data Assimilation.” IEEE Geoscience and Remote Sensing Letters 15 (4): 498–502. https://doi.org/10.1109/LGRS.2018.2805259.

Bolinger, Rebecca A., Christian D. Kummerow, and Nolan J. Doesken. 2014. “Attribution and Characteristics of Wet and Dry Seasons in the Upper Colorado River Basin.” Journal of Climate 27 (23): 8661–73. https://doi.org/10.1175/JCLI-D-13-00618.1.

Bracken, Cameron W. 2011. “Seasonal to Inter-Annual Streamflow Simulation and Forecasting on the Upper Colorado River Basin and Implications for Water Resources Management.” Boulder, CO: University of Colorado. https://www.colorado.edu/cadswes/sites/default/files/attached-files/bracken-ms_thesis-2011.pdf.

Bracken, Cameron W., Balaji Rajagopalan, and Connie A. Woodhouse. 2016. "A Bayesian Hierarchical Nonhomogeneous Hidden Markov Model for Multisite Streamflow Reconstructions." Water Resources Research 52 (10): 7837–50. https://doi.org/10.1002/2016WR018887.

Bradley, A. Allen, Mohamed Habib, and Stuart S. Schwartz. 2015. "Climate Index Weighting of Ensemble Streamflow Forecasts Using a Simple Bayesian Approach." Water Resources Research 51 (9): 7382–7400. https://doi.org/10.1002/2014WR016811.

Bradley, R. S., H. F. Diaz, G. N. Kiladis, and J. K. Eischeid. 1987. "ENSO Signal in Continental Temperature and Precipitation Records." Nature 327 (6122): 497–501. https://doi.org/10.1038/327497a0.

Braganza, Karl, Joëlle L. Gergis, Scott B. Power, James S. Risbey, and Anthony M. Fowler. 2009. "A Multiproxy Index of the El Niño–Southern Oscillation, A.D. 1525–1982." Journal of Geophysical Research 114 (D5). https://doi.org/10.1029/2008JD010896.

Brahney, J., A. P. Ballantyne, C. Sievers, and J. C. Neff. 2013. "Increasing Ca2+ Deposition in the Western US: The Role of Mineral Aerosols." Aeolian Research 10 (September): 77–87. https://doi.org/10.1016/j.aeolia.2013.04.003.

Bras, Rafael L., and Ignacio Rodríguez-Iturbe. 1985. Random Functions and Hydrology. Reading, Mass: Addison-Wesley.

Breheny, Patrick. 2012. "Kernel Density Estimation." Slides, University of Kentucky, Lexington, October. https://web.as.uky.edu/statistics/users/pbreheny/621/F12/notes/10-18.pdf.

Brekke, Levi D. 2009. "Long-Term Planning Hydrology Based on Various Blends of Instrumental Records, Paleoclimate, and Projected Climate Information." US Bureau of Reclamation. https://www.usbr.gov/research/projects/detail.cfm?id=6395.

———. 2011. "Addressing Climate Change in Long-Term Water Resources Planning and Management." CWTS-10-02. US Army Corps of Engineers Civil Works Technical Series. US Army Corps of Engineers. https://www.usbr.gov/climate/userneeds/docs/LTdoc.pdf.

Brekke, Levi D., Michael D. Dettinger, Edwin P. Maurer, and Michael Anderson. 2008. "Significance of Model Credibility in Estimating Climate Projection Distributions for Regional Hydroclimatological Risk Assessments." Climatic Change 89 (3–4): 371–94. https://doi.org/10.1007/s10584-007-9388-3.

Brekke, Levi D., Julie E. Kiang, J. Rolf Olsen, Roger S. Pulwarty, David A. Raff, D. Phil Turnipseed, Robert S. Webb, and Kathleen D. White. 2009. "Climate Change and Water Resources Management: A Federal Perspective." Circular 1331. Reston, Va: U.S. Geological Survey.

Brown, Casey, and Robert L. Wilby. 2012. "An Alternate Approach to Assessing Climate Risks." Eos, Transactions American Geophysical Union 93 (41): 401–2. https://doi.org/10.1029/2012EO410001.

Brown, David P., and Andrew C. Comrie. 2004. "A Winter Precipitation 'Dipole' in the Western United States Associated with Multidecadal ENSO Variability." Geophysical Research Letters 31 (9): n/a-n/a. https://doi.org/10.1029/2003GL018726.

Brown, Tim, John D. Horel, Gregory D. McCurdy, and Matthew G. Fearson. 2011. "Report to the NWCG: What Is the Appropriate RAWS Network?" Program for Climate, Ecosystem and Fire Applications (CEFA) Report 1101. National Wildfire Coordinating Group. https://www.nwcg.gov/publications/1003.

Bryant, Ann C., Thomas H. Painter, Jeffrey S. Deems, and Stacie M. Bender. 2013. "Impact of Dust Radiative Forcing in Snow on Accuracy of Operational Runoff Prediction in the Upper Colorado River Basin." Geophysical Research Letters 40 (15): 3945–49. https://doi.org/10.1002/grl.50773.

CADSWES. 2018. "RiverWare Technical Documentation Version 7.4, Objects." http://riverware.org/PDF/RiverWare/documentation/Objects.pdf.

California Dept. of Water Resources. 2016. “Description of Analytical Tools, Water Evaluation and Planning (WEAP).” https://water.ca.gov/LegacyFiles/waterplan/docs/tools/descriptions/WEAP-description.pdf.

———. 2019. “WRIMS: Water Resource Integrated Modeling System.” 2019. http://water.ca.gov/Library/Modeling-and-Analysis/Modeling-Platforms/Water-Resource-Integrated-Modeling-System.

Carroll, Rosemary W. H., Lindsay A. Bearup, Wendy Brown, Wenming Dong, Markus Bill, and Kenneth H. Willlams. 2018. “Factors Controlling Seasonal Groundwater and Solute Flux from Snow-Dominated Basins.” Hydrological Processes 32 (14): 2187–2202. https://doi.org/10.1002/hyp.13151.

Castle, Stephanie L., Brian F. Thomas, John T. Reager, Matthew Rodell, Sean C. Swenson, and James S. Famiglietti. 2014. “Groundwater Depletion during Drought Threatens Future Water Security of the Colorado River Basin.” Geophysical Research Letters 41 (16): 5904–11. https://doi.org/10.1002/2014GL061055.

Cawthorne, Dylan. 2017. “2017 Colorado River Hydrology Research Symposium,” 43.

Cayan, Daniel R., Michael D. Dettinger, David W. Pierce, Tapash Das, Noah Knowles, F. Martin Ralph, and Edwin Sumargo. 2016. “Natural Variability Anthropogenic Climate Change and Impacts on Water Availability and Flood Extremes in the Western United States.” In Water Policy and Planning in a Variable and Changing Climate. Drought and Water Crises. CRC Press. https://doi.org/10.1201/b19534.

Cayan, Daniel R., Susan A. Kammerdiener, Michael D. Dettinger, Joseph M. Caprio, and David H. Peterson. 2001. “Changes in the Onset of Spring in the Western United States.” Bulletin of the American Meteorological Society 82 (3): 399–416. https://doi.org/10.1175/1520-0477(2001)082<0399:CITOOS>2.3.CO;2.

Cayan, Daniel R., Kelly T. Redmond, and Laurence G. Riddle. 1999. “ENSO and Hydrologic Extremes in the Western United States.” Journal of Climate 12 (9): 2881–93. https://doi.org/10.1175/1520-0442(1999)012<2881:EAHEIT>2.0.CO;2.

Chen, Xianyao, and John M. Wallace. 2016. “Orthogonal PDO and ENSO Indices.” Journal of Climate 29 (10): 3883–92. https://doi.org/10.1175/JCLI-D-15-0684.1.

Christensen, Niklas S., and Dennis P. Lettenmaier. 2007. “A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin.” Hydrol. Earth Syst. Sci., 18.

Christensen, Niklas S., Andrew W. Wood, Nathalie Voisin, Dennis P. Lettenmaier, and Richard N. Palmer. 2004. “The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin.” Climatic Change 62 (1–3): 337–63. https://doi.org/10.1023/B:CLIM.0000013684.13621.1f.

Clark, Martyn P., Marc F. P. Bierkens, Luis Samaniego, Ross A. Woods, Remko Uijlenhoet, Katrina E. Bennett, Valentijn R. N. Pauwels, Xitian Cai, Andrew W. Wood, and Christa D. Peters-Lidard. 2017. “The Evolution of Process-Based Hydrologic Models: Historical Challenges and the Collective Quest for Physical Realism.” Hydrology and Earth System Sciences 21 (7): 3427–40. https://doi.org/10.5194/hess-21-3427-2017.

Clark, Martyn P., Subhrendu Gangopadhyay, Lauren E. Hay, Balaji Rajagopalan, and Robert Wilby. 2004. “The Schaake Shuffle: A Method for Reconstructing Space–Time Variability in Forecasted Precipitation and Temperature Fields.” Journal of Hydrometeorology 5 (1): 243–62. https://doi.org/10.1175/1525-7541(2004)005<0243:TSSAMF>2.0.CO;2.

Clark, Martyn P., and Lauren E. Hay. 2004. “Use of Medium-Range Numerical Weather Prediction Model Output to Produce Forecasts of Streamflow.” Journal of Hydrometeorology 5 (15): 32. https://doi.org/doi:10.1175/1525-7541(2004)005<0015:UOMNWP>2.0.CO;2.

Clark, Martyn P., Bart Nijssen, Jessica D. Lundquist, Dmitri Kavetski, David E. Rupp, Ross A. Woods, Jim E. Freer, et al. 2015. "A Unified Approach for Process-Based Hydrologic Modeling: 1. Modeling Concept." Water Resources Research 51 (4): 2498–2514. https://doi.org/10.1002/2015WR017198.

Clark, Martyn P., and Andrew G. Slater. 2006. "Probabilistic Quantitative Precipitation Estimation in Complex Terrain." Journal of Hydrometeorology 7 (1): 3–22. https://doi.org/10.1175/JHM474.1.

Clark, Martyn P., Robert L. Wilby, Ethan D. Gutmann, Julie A. Vano, Subhrendu Gangopadhyay, Andrew W. Wood, Hayley J. Fowler, Christel Prudhomme, Jeffrey R. Arnold, and Levi D. Brekke. 2016. "Characterizing Uncertainty of the Hydrologic Impacts of Climate Change." Current Climate Change Reports 2 (2): 55–64. https://doi.org/10.1007/s40641-016-0034-x.

Clayton, Jordan, Steven Quiring, Tyson Ochsner, Michael Cosh, C. Baker, Trent Ford, John Bolten, and Molly Woloszyn. 2019. "Building a One-Stop Shop for Soil Moisture Information." Eos 100 (June). https://doi.org/10.1029/2019EO123631.

CLIMAS and WWA. n.d. "TreeFlow – Streamflow Reconstructions from Tree Rings." TreeFlow. Accessed June 27, 2019. https://www.treeflow.info/.

Cloke, Hannah L., and Florian Pappenberger. 2009. "Ensemble Flood Forecasting: A Review." Journal of Hydrology 375 (3–4): 613–26. https://doi.org/10.1016/j.jhydrol.2009.06.005.

Clow, David W. 2010. "Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming." Journal of Climate 23 (9): 2293–2306. https://doi.org/10.1175/2009JCLI2951.1.

Clow, David W., Leora Nanus, Kristine L. Verdin, and Jeffrey Schmidt. 2012. "Evaluation of SNODAS Snow Depth and Snow Water Equivalent Estimates for the Colorado Rocky Mountains, USA: EVALUATION OF SNODAS." Hydrological Processes 26 (17): 2583–91. https://doi.org/10.1002/hyp.9385.

Clow, David W., Mark W. Williams, and Paul F. Schuster. 2016. "Increasing Aeolian Dust Deposition to Snowpacks in the Rocky Mountains Inferred from Snowpack, Wet Deposition, and Aerosol Chemistry." Atmospheric Environment 146 (December): 183–94. https://doi.org/10.1016/j.atmosenv.2016.06.076.

Coats, Sloan, Jason E. Smerdon, Benjamin I. Cook, and Richard Seager. 2015. "Are Simulated Megadroughts in the North American Southwest Forced?" Journal of Climate 28 (1): 124–42. https://doi.org/10.1175/JCLI-D-14-00071.1.

Coats, Sloan, Jason E. Smerdon, Benjamin I. Cook, Richard Seager, Edward R. Cook, and K. J. Anchukaitis. 2016. "Internal Ocean-Atmosphere Variability Drives Megadroughts in Western North America." Geophysical Research Letters 43 (18): 9886–94. https://doi.org/10.1002/2016GL070105.

"CoCoRaHS: Community Collaborative Rain, Hail & Snow Network." n.d. Accessed November 13, 2019. https://www.cocorahs.org/.

Cohn, Timothy, Julie Kiang, and Robert Mason. 2013. "Estimating Discharge Measurement Uncertainty Using the Interpolated Variance Estimator." Journal of Hydraulic Engineering 139 (5): 502–10. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000695.

Colorado State University. 2017. "MODSIM-DSS." 2017. http://modsim.engr.colostate.edu/.

Colorado State University. 2019. "CoAgMET." CoAgMET Colorado's Mesonet. 2019. https://coagmet.colostate.edu/.

Colorado Water Conservation Board. 2012. "Colorado River Water Availability Study." Colorado Water Conservation Board. http://cwcbweblink.state.co.us/WebLink/ElectronicFile.aspx?docid=158319&searchid=78f0eafa-0b8f-4d8a-9ff3-faf67cc82f52&dbid=0.

Cook, Benjamin I., Toby R. Ault, and Jason E. Smerdon. 2015. "Unprecedented 21st Century Drought Risk in the American Southwest and Central Plains." Science Advances 1 (1): e1400082. https://doi.org/10.1126/sciadv.1400082.

Cook, Benjamin I., Richard Seager, and Ron L. Miller. 2011. "On the Causes and Dynamics of the Early Twentieth-Century North American Pluvial." Journal of Climate 24 (19): 5043–60. https://doi.org/10.1175/2011JCLI4201.1.

Cook, Edward R. 2004. "Long-Term Aridity Changes in the Western United States." Science 306 (5698): 1015–18. https://doi.org/10.1126/science.1102586.

Cook, Edward R., and Leonardas Kairiūkštis, eds. 1990. Methods of Dendrochronology: Applications in the Environmental Science. Dordrecht, Netherlands ; Boston : [S.l.]: Kluwer Academic Publishers ; International Institute for Applied Systems Analysis.

Cook, Edward R., Richard Seager, Mark A. Cane, and David W. Stahle. 2007. "North American Drought: Reconstructions, Causes, and Consequences." Earth-Science Reviews 81 (1–2): 93–134. https://doi.org/10.1016/j.earscirev.2006.12.002.

Cook, Edward R., Richard Seager, Richard R. Heim, Russell S. Vose, Celine Herweijer, and Connie Woodhouse. 2010. "Megadroughts in North America: Placing IPCC Projections of Hydroclimatic Change in a Long-Term Palaeoclimate Context." Journal of Quaternary Science 25 (1): 48–61. https://doi.org/10.1002/jqs.1303.

Cosgrove, Brian A. 2003. "Real-Time and Retrospective Forcing in the North American Land Data Assimilation System (NLDAS) Project." Journal of Geophysical Research 108 (D22). https://doi.org/10.1029/2002JD003118.

Cowan, Michael S., R. Wayne Cheney, and Jeffrey C. Addiego. 1981. "An Executive Summary of the Colorado River Simulation System." Denver, Colorado: Reclamation.

CWCB. 2012. "Colorado River Water Availability Study." Colorado Water Conservation Board. https://dnrweblink.state.co.us/cwcb/0/doc/158319/Electronic.aspx?searchid=78f0eafa-0b8f-4d8a-9ff3-faf67cc82f52.

Daly, Christopher. 2006. "Guidelines for Assessing the Suitability of Spatial Climate Data Sets." International Journal of Climatology 26 (6): 707–21. https://doi.org/10.1002/joc.1322.

Daly, Christopher, Wayne P. Gibson, George H. Taylor, Gregory L. Johnson, and Phillip Pasteris. 2002. "A Knowledge-Based Approach to the Statistical Mapping of Climate." Climate Research 22: 99–113. https://doi.org/10.3354/cr022099.

Daly, Christopher, Michael Halbleib, Joseph I. Smith, Wayne P. Gibson, Matthew K. Doggett, George H. Taylor, Jan Curtis, and Phillip P. Pasteris. 2008. "Physiographically Sensitive Mapping of Climatological Temperature and Precipitation across the Conterminous United States." International Journal of Climatology 28 (15): 2031–64. https://doi.org/10.1002/joc.1688.

Daly, Christopher, Ronald P. Neilson, and Donald L. Phillips. 1994. "A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainout Terrain." Journal of Applied Meteorology 33: 140–58.

Daly, Christopher, Joseph I. Smith, and Keith V. Olson. 2015. "Mapping Atmospheric Moisture Climatologies across the Conterminous United States." Edited by Robert Guralnick. PLOS ONE 10 (10): e0141140. https://doi.org/10.1371/journal.pone.0141140.

Daly, Christopher, George Taylor, and Wayne Gibson. 1997. "The PRISM Approach to Mapping Precipitation and Temperature." In Proceedings,10th AMS Conference on Applied Climatology, 20–23.

D'Arrigo, Rosanne, R. Villalba, and G. Wiles. 2001. "Tree-Ring Estimates of Pacific Decadal Climate Variability." Climate Dynamics 18 (3–4): 219–24. https://doi.org/10.1007/s003820100177.

Das, Tapash, David W. Pierce, Daniel R. Cayan, Julie A. Vano, and Dennis P. Lettenmaier. 2011. "The Importance of Warm Season Warming to Western U.S. Streamflow Changes." Geophysical Research Letters 38 (23): n/a-n/a. https://doi.org/10.1029/2011GL049660.

Davis, Gary. 2007. "History of the NOAA Satellite Program." Journal of Applied Remote Sensing 1 (1): 012504. https://doi.org/10.1117/1.2642347.

Dawson, Nicholas, Patrick Broxton, and Xubin Zeng. 2018. "Evaluation of Remotely Sensed Snow Water Equivalent and Snow Cover Extent over the Contiguous United States." Journal of Hydrometeorology 19 (11): 1777–91. https://doi.org/10.1175/JHM-D-18-0007.1.

Day, Gerald N. 1985. "Extended Streamflow Forecasting Using NWSRFS." Journal of Water Resources Planning and Management 111 (2): 157–70. https://doi.org/10.1061/(ASCE)0733-9496(1985)111:2(157).

DeChant, Caleb M., and Hamid Moradkhani. 2011a. "Radiance Data Assimilation for Operational Snow and Streamflow Forecasting." Advances in Water Resources 34 (3): 351–64. https://doi.org/10.1016/j.advwatres.2010.12.009.

———. 2011b. "Improving the Characterization of Initial Condition for Ensemble Streamflow Prediction Using Data Assimilation." Hydrology and Earth System Sciences 15 (11): 3399–3410. https://doi.org/10.5194/hess-15-3399-2011.

Deems, Jeffrey S., and Alan F. Hamlet. 2010. "Historical Meteorological Driving Data Set," 13.

Deems, Jeffrey S., Thomas H. Painter, Joseph J. Barsugli, Jayne Belnap, and Bradley Udall. 2013. "Combined Impacts of Current and Future Dust Deposition and Regional Warming on Colorado River Basin Snow Dynamics and Hydrology." Hydrology and Earth System Sciences 17 (11): 4401–13. https://doi.org/10.5194/hess-17-4401-2013.

DelSole, Timothy, and Jagadish Shukla. 2009. "Artificial Skill Due to Predictor Screening." Journal of Climate 22 (2): 331–45. https://doi.org/10.1175/2008JCLI2414.1.

Demargne, Julie, Mary Mullusky, Larry Lowe, James Coe, Kevin Werner, Brenda Alcorn, Lisa Holts, et al. 2009. "Towards Standard Verification Strategies For Operational Hydrologic Forecasting: Report of the NWS Hydrologic Forecast Verification Team." Silver Spring, Maryland. https://www.nws.noaa.gov/oh/rfcdev/docs/NWS-Hydrologic-Forecast-Verification-Team_Final-report_Sep09.pdf.

Demargne, Julie, Limin Wu, Satish K. Regonda, James D. Brown, Haksu Lee, Minxue He, Dong-Jun Seo, et al. 2014. "The Science of NOAA's Operational Hydrologic Ensemble Forecast Service." Bulletin of the American Meteorological Society 95 (1): 79–98. https://doi.org/10.1175/BAMS-D-12-00081.1.

Deser, Clara, Reto Knutti, Susan Solomon, and Adam S. Phillips. 2012. "Communication of the Role of Natural Variability in Future North American Climate." Nature Climate Change 2 (11): 775–79. https://doi.org/10.1038/nclimate1562.

Deser, Clara, Adam Phillips, Vincent Bourdette, and Haiyan Teng. 2012. "Uncertainty in Climate Change Projections: The Role of Internal Variability." Climate Dynamics 38 (3–4): 527–46. https://doi.org/10.1007/s00382-010-0977-x.

DHI. 2019. "MIKE HYDRO Basin." February 2019. https://www.mikepoweredbydhi.com/products/mike-hydro-basin.

Diamond, Howard J., Thomas R. Karl, Michael A. Palecki, C. Bruce Baker, Jesse E. Bell, Ronald D. Leeper, David R. Easterling, et al. 2013. "U.S. Climate Reference Network After One Decade of Operations," 14.

Dirmeyer, Paul A., and Subhadeep Halder. 2016. "Sensitivity of Numerical Weather Forecasts to Initial Soil Moisture Variations in CFSv2." Weather and Forecasting 31 (6): 1973–83. https://doi.org/10.1175/WAF-D-16-0049.1.

Doesken, Nolan J., and Henry W. Reges. 2010. "The Value of the Citizen Weather Observer." Weatherwise 63 (6): 30–37.

Dorigo, Wouter, Peter Oevelen, Wolfgang Wagner, Matthias Drusch, Susanne Mecklenburg, Alan Robock, and Thomas Jackson. 2011. "A New International Network for in Situ Soil Moisture Data." Eos, Transactions American Geophysical Union 92 (17): 141–42. https://doi.org/10.1029/2011EO170001.

Duan, Qingyun, Soroosh Sorooshian, and Vijai K. Gupta. 1994. "Optimal Use of the SCE-UA Global Optimization Method for Calibrating Watershed Models." Journal of Hydrology 158 (3): 265–84. https://doi.org/10.1016/0022-1694(94)90057-4.

Duniway, Michael C., Alix A. Pfennigwerth, Stephen E. Fick, Travis W. Nauman, Jayne Belnap, and Nichole N. Barger. 2019. "Wind Erosion and Dust from US Drylands: A Review of Causes, Consequences, and Solutions in a Changing World." Ecosphere 10 (3): e02650. https://doi.org/10.1002/ecs2.2650.

Durre, Imke, Matthew J. Menne, Byron E. Gleason, Tamara G. Houston, and Russell S. Vose. 2010. "Comprehensive Automated Quality Assurance of Daily Surface Observations." Journal of Applied Meteorology and Climatology 49 (8): 1615–33. https://doi.org/10.1175/2010JAMC2375.1.

Emerton, Rebecca E., Ervin Zsoter, Louise Arnal, Hannah L. Cloke, Davide Muraro, Christel Prudhomme, Elisabeth M. Stephens, Peter Salamon, and Florian Pappenberger. 2018. "Developing a Global Operational Seasonal Hydro-Meteorological Forecasting System: GloFAS-Seasonal v1.0." Geoscientific Model Development 11 (8): 3327–46. https://doi.org/10.5194/gmd-11-3327-2018.

Erkyihun, Solomon Tassew, Balaji Rajagopalan, Edith Zagona, Upmanu Lall, and Kenneth Nowak. 2016. "Wavelet-Based Time Series Bootstrap Model for Multidecadal Streamflow Simulation Using Climate Indicators." Water Resources Research 52 (5): 4061–77. https://doi.org/10.1002/2016WR018696.

Evan, Amato T. 2018. "A New Method to Characterize Changes in the Seasonal Cycle of Snowpack." Journal of Applied Meteorology and Climatology, December. https://doi.org/10.1175/JAMC-D-18-0150.1.

Eyring, Veronika, Peter M. Cox, Gregory M. Flato, Peter J. Gleckler, Gab Abramowitz, Peter Caldwell, William D. Collins, et al. 2019. "Taking Climate Model Evaluation to the next Level." Nature Climate Change 9 (2): 102–10. https://doi.org/10.1038/s41558-018-0355-y.

Fan, Y., Martyn P. Clark, D. M. Lawrence, S. Swenson, L. E. Band, S. L. Brantley, P. D. Brooks, et al. 2019. "Hillslope Hydrology in Global Change Research and Earth System Modeling." Water Resources Research 55 (2): 1737–72. https://doi.org/10.1029/2018WR023903.

Federal Aviation Administration (FAA). 2019. "Surface Weather Observation Stations (ASOS/AWOS)." Surface Weather Observation Stations (ASOS/AWOS). 2019. https://www.faa.gov/air_traffic/weather/asos/.

Ficklin, Darren L., Iris T. Stewart, and Edwin P. Maurer. 2013. "Climate Change Impacts on Streamflow and Subbasin-Scale Hydrology in the Upper Colorado River Basin." Edited by Vishal Shah. PLoS ONE 8 (8): e71297. https://doi.org/10.1371/journal.pone.0071297.

Finch, J. W. 2001. "A Comparison between Measured and Modelled Open Water Evaporation from a Reservoir in South-East England." Hydrological Processes 15 (14): 2771–78. https://doi.org/10.1002/hyp.267.

Flato, Gregory M., J. Marotzke, B. Abiodun, P. Braconnot, S. C. Chou, W. Collins, P. Cox, et al. 2013. "Evaluation of Climate Models." In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, 741–882. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.020.

Fleming, Sean W., and Angus G. Goodbody. 2019. "A Machine Learning Metasystem for Robust Probabilistic Nonlinear Regression-Based Forecasting of Seasonal Water Availability in the US West." IEEE Access 7: 119943–64. https://doi.org/10.1109/ACCESS.2019.2936989.

Flossmann, Andrea I., Michael Manton, Ali Abshaev, Roelof Bruintjes, Masataka Murakami, Thara Prabhakaran, and Zhanyu Yao. 2019. "Review of Advances in Precipitation Enhancement Research." Bulletin of the American Meteorological Society 100 (8): 1465–80. https://doi.org/10.1175/BAMS-D-18-0160.1.

Foster, Lauren M., Lindsay A. Bearup, Noah P. Molotch, Paul Brooks, and Reed M. Maxwell. 2016. "Energy Budget Increases Reduce Mean Streamflow More than Snow–Rain Transitions: Using Integrated Modeling to Isolate Climate Change Impacts on Rocky Mountain Hydrology." Environmental Research Letters 11 (4): 044015. https://doi.org/10.1088/1748-9326/11/4/044015.

Franz, Kristie J., Terrie S. Hogue, and Soroosh Sorooshian. 2008. "Operational Snow Modeling: Addressing the Challenges of an Energy Balance Model for National Weather Service Forecasts." Journal of Hydrology 360: 48–66.

French, Jeffrey R., Katja Friedrich, Sarah A. Tessendorf, Robert M. Rauber, Bart Geerts, Roy M. Rasmussen, Lulin Xue, Melvin L. Kunkel, and Derek R. Blestrud. 2018. "Precipitation Formation from Orographic Cloud Seeding." Proceedings of the National Academy of Sciences 115 (6): 1168–73. https://doi.org/10.1073/pnas.1716995115.

Freund, Mandy B., Benjamin J. Henley, David J. Karoly, Helen V. McGregor, Nerilie J. Abram, and Dietmar Dommenget. 2019. "Higher Frequency of Central Pacific El Niño Events in Recent Decades Relative to Past Centuries." Nature Geoscience 12 (6): 450–55. https://doi.org/10.1038/s41561-019-0353-3.

Frevert, Donald K., and R. Wayne Cheney. 1988. "Alternative Methods of Generating Hydrologic Data for Reservoir Optimization." In Computerized Decision Support Systems for Water Managers. New York, NY: American Society of Civil Engineers.

Friedrich, Katja, Robert L. Grossman, Justin Huntington, Peter D. Blanken, John Lenters, Kathleen D. Holman, David Gochis, et al. 2018. "Reservoir Evaporation in the Western United States: Current Science, Challenges, and Future Needs." Bulletin of the American Meteorological Society 99 (1): 167–87. https://doi.org/10.1175/BAMS-D-15-00224.1.

Fritts, Harold C. 1976. Tree Rings and Climate. London ; New York: Academic Press.

Fritts, Harold C., J. Guiot, and G. A. Gordon. 1990. "Verification. in Methods of Dendrochronology: Applications in the Environmental Sciences." In Methods of Dendrochronology: Applications in the Environmental Sciences. Edited by E. R. Cook and L. A. Kairiukstis, 178–185. Dordrecht: Kluwer Academic Publishers.

Fritze, Holger, Iris T. Stewart, and Edzer Pebesma. 2011. "Shifts in Western North American Snowmelt Runoff Regimes for the Recent Warm Decades." Journal of Hydrometeorology 12 (5): 989–1006. https://doi.org/10.1175/2011JHM1360.1.

Fyfe, John C., Chris Derksen, Lawrence Mudryk, Gregory M. Flato, Benjamin D. Santer, Neil C. Swart, Noah P. Molotch, et al. 2017. "Large Near-Term Projected Snowpack Loss over the Western United States." Nature Communications 8 (April): 14996. https://doi.org/10.1038/ncomms14996.

Gangopadhyay, Subhrendu, Benjamin L. Harding, Balaji Rajagopalan, Jeffrey J. Lukas, and Terrance J. Fulp. 2009. "A Nonparametric Approach for Paleohydrologic Reconstruction of Annual Streamflow Ensembles." Water Resources Research 45 (6). https://doi.org/10.1029/2008WR007201.

Gangopadhyay, Subhrendu, Gregory J. McCabe, and Connie A. Woodhouse. 2015. "Beyond Annual Streamflow Reconstructions for the Upper Colorado River Basin: A Paleo-Water-Balance Approach." Water Resources Research 51 (12): 9763–74. https://doi.org/10.1002/2015WR017283.

Gao, Bo-cai. 1996. "NDWI—A Normalized Difference Water Index for Remote Sensing of Vegetation Liquid Water from Space." Remote Sensing of Environment 58 (3): 257–66. https://doi.org/10.1016/S0034-4257(96)00067-3.

Gao, Yanhong, Julie A. Vano, Chunmei Zhu, and Dennis P. Lettenmaier. 2011. "Evaluating Climate Change over the Colorado River Basin Using Regional Climate Models." Journal of Geophysical Research 116 (D13). https://doi.org/10.1029/2010JD015278.

Garbrecht, Jurgen D., and Thomas C. Piechota. 2005. Climate Variations, Climate Change, and Water Resources Engineering. American Society of Civil Engineers. https://doi.org/10.1061/9780784408247.

Garen, David C. 1992. "Improved Techniques in Regression-Based Streamflow Volume Forecasting." Journal of Water Resources Planning and Management 118 (6): 654–70. https://doi.org/10.1061/(ASCE)0733-9496(1992)118:6(654).

Garen, David C., and Thomas C. Pagano. 2007. "Statistical Techniques Used in the VIPER Water Supply Forecasting Software." Technical Note TN-210-SSWSF-2. Technical Note. Natural Resource Conservation Service. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=34239.wba.

Garfin, Gregg, Angela Jardine, Robert Merideth, Mary Black, and Sarah LeRoy, eds. 2013. Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. Washington, DC: Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-484-0.

Gates, W. Lawrence, James S. Boyle, Curt Covey, Clyde G. Dease, Charles M. Doutriaux, Robert S. Drach, Michael Fiorino, et al. 1992. "An Overview of the Results of the Atmospheric Model Intercomparison Project (AMIP I)." Bulletin of the American Meteorological Society 73: 1962–70. https://doi.org/10.1175/1520-0477(1999)080<0029:AOOTRO>2.0.CO;2.

Gedalof, Ze'ev, Nathan J. Mantua, and David L. Peterson. 2002. "A Multi-Century Perspective of Variability in the Pacific Decadal Oscillation: New Insights from Tree Rings and Coral." Geophysical Research Letters 29 (24): 57-1-57–4. https://doi.org/10.1029/2002GL015824.

Geerts, Bart, Qun Miao, Yang Yang, Roy Rasmussen, and Daniel Breed. 2010. "An Airborne Profiling Radar Study of the Impact of Glaciogenic Cloud Seeding on Snowfall from Winter Orographic Clouds." Journal of the Atmospheric Sciences 67 (10): 3286–3302. https://doi.org/10.1175/2010JAS3496.1.

Geerts, Bart, Binod Pokharel, Katja Friedrich, Dan Breed, Roy Rasmussen, Yang Yang, Qun Miao, Samuel Haimov, Bruce Boe, and Evan Kalina. 2013. "The AgI Seeding Cloud Impact Investigation (ASCII) Campaign 2012: Overview and Preliminary Results." Journal of Weather Modification 45: 20.

Georgakakos, Konstantine P., N. E. Graham, F.-Y. Cheng, C. Spencer, E. Shamir, A. P. Georgakakos, H. Yao, and M. Kistenmacher. 2012. "Value of Adaptive Water Resources Management in Northern California under Climatic Variability and Change: Dynamic Hydroclimatology." Journal of Hydrology 412–413 (January): 47–65. https://doi.org/10.1016/j.jhydrol.2011.04.032.

Gergis, Joëlle, Karl Braganza, Anthony Fowler, Scott Mooney, and James Risbey. 2006. "Reconstructing El Niño–Southern Oscillation (ENSO) from High-Resolution Palaeoarchives." Journal of Quaternary Science 21 (7): 707–22. https://doi.org/10.1002/jqs.1070.

Gershunov, Alexander, and Tim P. Barnett. 1998. "Interdecadal Modulation of ENSO Teleconnections I." Bulletin of the American Meteorological Society 79 (12): 12.

Gillies, Robert R., Oi-Yu Chung, Shih-Yu Wang, R. Justin DeRose, and Yan Sun. 2015. "Added Value from 576 Years of Tree-Ring Records in the Prediction of the Great Salt Lake Level." Journal of Hydrology 529 (October): 962–68. https://doi.org/10.1016/j.jhydrol.2015.08.058.

Gillies, Robert R., Oi-Yu Chung, Shih-Yu Wang, and Piotr Kokoszka. 2011. "Incorporation of Pacific SSTs in a Time Series Model toward a Longer-Term Forecast for the Great Salt Lake Elevation." Journal of Hydrometeorology 12 (3): 474–80. https://doi.org/10.1175/2010JHM1352.1.

Giorgi, Filippo, and Linda O. Mearns. 1991. "Approaches to the Simulation of Regional Climate Change: A Review." Reviews of Geophysics 29 (2): 191. https://doi.org/10.1029/90RG02636.

Gleckler, P. J., K. E. Taylor, and C. Doutriaux. 2008. "Performance Metrics for Climate Models." Journal of Geophysical Research 113 (D6). https://doi.org/10.1029/2007JD008972.

Gobena, A. K., and T. Y. Gan. 2010. "Incorporation of Seasonal Climate Forecasts in the Ensemble Streamflow Prediction System." Journal of Hydrology 385 (1): 336–52. https://doi.org/10.1016/j.jhydrol.2010.03.002.

Gochis, David J., W. Yu, and D. N. Yates. 2015. "The WRF-Hydro Model Technical Description and User's Guide, Version 3.0." http://www.ral.ucar.edu/projects/wrf_hydro/.

Gold, David. 2017. "An Introduction to Copulas." Water Programming: A Collaborative Research Blog (blog). November 11, 2017. https://waterprogramming.wordpress.com/2017/11/11/an-introduction-to-copulas/.

Gonzalez, Patrick, G. M. Garfin, D. D. Breshears, K. M. Brooks, H. E. Brown, E. H. Elias, A. Gunasekara, et al. 2018. "Fourth National Climate Assessment-Chapter 25: Southwest." https://nca2018.globalchange.govhttps://nca2018.globalchange.gov/chapter/25.

Goodison, B. E., P. Y. T. Louie, and D. Yang. 1998. "WMO Solid Precipitation Measurement Intercomparison--Final Report," 318.

Grantz, Katrina, Balaji Rajagopalan, Martyn P. Clark, and Edith Zagona. 2005. "A Technique for Incorporating Large-Scale Climate Information in Basin-Scale Ensemble Streamflow Forecasts." Water Resources Research 41 (10). https://doi.org/10.1029/2004WR003467.

———. 2007. "Seasonal Shifts in the North American Monsoon." Journal of Climate 20 (9): 1923–35. https://doi.org/10.1175/JCLI4091.1.

Gray, Stephen T., Lisa J. Graumlich, Julio L. Betancourt, and Gregory T. Pederson. 2004. "A Tree-Ring Based Reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D." Geophysical Research Letters 31 (12): n/a-n/a. https://doi.org/10.1029/2004GL019932.

Gray, Stephen T., and Gregory J. McCabe. 2010. "A Combined Water Balance and Tree Ring Approach to Understanding the Potential Hydrologic Effects of Climate Change in the Central Rocky Mountain Region." Water Resources Research 46 (5). https://doi.org/10.1029/2008WR007650.

Grayson, Rodger B., Ian D. Moore, and Thomas A. McMahon. 1992a. "Physically Based Hydrologic Modeling: 1. A Terrain-Based Model for Investigative Purposes." Water Resources Research 28 (10): 2639–58. https://doi.org/10.1029/92WR01258.

———. 1992b. "Physically Based Hydrologic Modeling: 2. Is the Concept Realistic?" Water Resources Research 28 (10): 2659–66. https://doi.org/10.1029/92WR01259.

Groisman, Pavel Ya, and David R. Easterling. 1994. "Variability and Trends of Total Precipitation and Snowfall over the United States and Canada." Journal of Climate 7: 184–204.

Grygier, J. C., and Jery R. Stedinger. 1990. "SPIGOT, A Synthetic Streamflow Generation Software Package." Ithaca, NY: School of Civil and Environmental Engineering, Cornell University.

Guan, Bin, Noah P. Molotch, Duane E. Waliser, Steven M. Jepsen, Thomas H. Painter, and Jeff Dozier. 2013. "Snow Water Equivalent in the Sierra Nevada: Blending Snow Sensor Observations with Snowmelt Model Simulations." Water Resources Research 49 (8): 5029–46. https://doi.org/10.1002/wrcr.20387.

Guan, Bin, Duane E. Waliser, Noah P. Molotch, Eric J. Fetzer, and Paul J. Neiman. 2012. "Does the Madden–Julian Oscillation Influence Wintertime Atmospheric Rivers and Snowpack in the Sierra Nevada?" Monthly Weather Review 140 (2): 325–42. https://doi.org/10.1175/MWR-D-11-00087.1.

Guentchev, Galina, Joseph J. Barsugli, and Jon Eischeid. 2010. "Homogeneity of Gridded Precipitation Datasets for the Colorado River Basin." Journal of Applied Meteorology and Climatology 49 (12): 2404–15. https://doi.org/10.1175/2010JAMC2484.1.

Guo, Ruixia, Clara Deser, Laurent Terray, and Flavio Lehner. 2019. "Human Influence on Winter Precipitation Trends (1921–2015) over North America and Eurasia Revealed by Dynamical Adjustment." Geophysical Research Letters 46 (6): 3426–34. https://doi.org/10.1029/2018GL081316.

Gutmann, Ethan D., Idar Barstad, Martyn P. Clark, Jeffrey Arnold, and Roy Rasmussen. 2016. "The Intermediate Complexity Atmospheric Research Model (ICAR)." Journal of Hydrometeorology 17 (3): 957–73. https://doi.org/10.1175/JHM-D-15-0155.1.

Gutmann, Ethan D., Tom Pruitt, Martyn P. Clark, Levi Brekke, Jeffrey R. Arnold, David A. Raff, and Roy M. Rasmussen. 2014. "An Intercomparison of Statistical Downscaling Methods Used for Water Resource Assessments in the United States." Water Resources Research 50 (9): 7167–86. https://doi.org/10.1002/2014WR015559.

Gutmann, Ethan D., Roy M. Rasmussen, Changhai Liu, Kyoko Ikeda, David J. Gochis, Martyn P. Clark, Jimy Dudhia, and Gregory Thompson. 2012. "A Comparison of Statistical and Dynamical Downscaling of Winter Precipitation over Complex Terrain." Journal of Climate 25 (1): 262–81. https://doi.org/10.1175/2011JCLI4109.1.

Haarsma, Reindert J., Malcolm J. Roberts, Pier Luigi Vidale, Catherine A. Senior, Alessio Bellucci, Qing Bao, Ping Chang, et al. 2016. "High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6." Geoscientific Model Development 9 (11): 4185–4208. https://doi.org/10.5194/gmd-9-4185-2016.

Haas, Amy. 2018. "Seventieth Annual Report of the Upper Colorado River Commission." Annual report 70. Salt Lake City, UT: Upper Colorado River Commission. http://www.ucrcommission.com/RepDoc/UCRCAnnualReports/70_UCRC_Annual_Report.pdf.

Hagedorn, Renate, Francisco J. Doblas-Reyes, and T. N. Palmer. 2005. "The Rationale behind the Success of Multi-Model Ensembles in Seasonal Forecasting – I. Basic Concept." Tellus A 57 (3): 219–33. https://doi.org/10.1111/j.1600-0870.2005.00103.x.

Hamel, Jama L. n.d. "AgriMet Quality Procedures.Doc."

Hamilton, A. S., and R. D. Moore. 2012. "Quantifying Uncertainty in Streamflow Records." Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques 37 (1): 3–21. https://doi.org/10.4296/cwrj3701865.

Hamlet, Alan F., and Dennis P. Lettenmaier. 1999. "Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals." Journal of Water Resources Planning and Management 125 (6): 333–41. https://doi.org/10.1061/(ASCE)0733-9496(1999)125:6(333).

———. 2005. "Production of Temporally Consistent Gridded Precipitation and Temperature Fields for the Continental United States." Journal of Hydrometeorology 6 (3): 330–36. https://doi.org/10.1175/JHM420.1.

Hamlet, Alan F., Philip W. Mote, Martyn P. Clark, and Dennis P. Lettenmaier. 2005. "Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States." Journal of Climate 18 (21): 4545–61. https://doi.org/10.1175/JCLI3538.1.

Hanson, Clayton L., Gregory L. Johnson, and Albert Rango. 1999. "Comparison of Precipitation Catch between Nine Measuring Systems." Journal of Hydrologic Engineering 4 (1): 70–76. https://doi.org/10.1061/(ASCE)1084-0699(1999)4:1(70).

Hao, Z., and V. P. Singh. 2012. "Entropy-Copula Method for Single-Site Monthly Streamflow Simulation." Water Resources Research 48 (6). https://doi.org/10.1029/2011WR011419.

Harding, Benjamin L., Andrew W. Wood, and James R. Prairie. 2012. "The Implications of Climate Change Scenario Selection for Future Streamflow Projection in the Upper Colorado River Basin." Hydrology and Earth System Sciences 16 (11): 3989–4007. https://doi.org/10.5194/hess-16-3989-2012.

Harding, Benjamin L. 2015. "Colorado River Water Availability Study, Phase II, Updating Climate Impacted Hydrology."

Harpold, Adrian A., Kent Sutcliffe, Jordan Clayton, Angus Goodbody, and Shareily Vazquez. 2017. "Does Including Soil Moisture Observations Improve Operational Streamflow Forecasts in Snow-Dominated Watersheds?" JAWRA Journal of the American Water Resources Association 53 (1): 179–96. https://doi.org/10.1111/1752-1688.12490.

Harrison, Brent, and Roger Bales. 2015. "Skill Assessment of Water Supply Outlooks in the Colorado River Basin." Hydrology 2 (3): 112–31. https://doi.org/10.3390/hydrology2030112.

Harwell, Glenn R. 2012. "Estimation of Evaporation from Open Water—A Review of Selected Studies, Summary of U.S. Army Corps of Engineers Data Collection and Methods, and Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas." Scientific Investigations Report 2012–5202. U.S. Geological Survey.

Hausfather, Zeke. 2019. "CMIP6-the next Generation of Climate Models Explained." Carbon Brief. 2019. https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained.

Hausfather, Zeke, Matthew J. Menne, Claude N. Williams, Troy Masters, Ronald Broberg, and David Jones. 2013. "Quantifying the Effect of Urbanization on U.S. Historical Climatology Network Temperature Record." Journal of Geophysical Research: Atmospheres 118 (2): 481–94. https://doi.org/10.1029/2012JD018509.

Hausfather, Zeke, and Glen P. Peters. 2020. "Emissions – the 'Business as Usual' Story Is Misleading." Nature 577 (7792): 618–20. https://doi.org/10.1038/d41586-020-00177-3.

Hawkins, Ed, and Rowan Sutton. 2009. "The Potential to Narrow Uncertainty in Regional Climate Predictions." Bulletin of the American Meteorological Society 90 (8): 1095–1108. https://doi.org/10.1175/2009BAMS2607.1.

Hedrick, A., H.-P. Marshall, A. Winstral, K. Elder, S. Yueh, and D. Cline. 2015. "Independent Evaluation of the Snodas Snow Depth Product Using Regional-Scale Lidar-Derived Measurements." The Cryosphere 9 (1): 13–23. https://doi.org/10.5194/tc-9-13-2015.

Helms, Douglas, Steven E. Phillips, and Paul F. Reich. 2008. The History of Snow Survey and Water Supply Forecasting-Interviews with U.S. Department of Agriculture Pioneers. USDA NRCS Historical Notes 8. US Department of Agriculture. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043910.pdf.

Henn, Brian, Andrew J. Newman, Ben Livneh, Christopher Daly, and Jessica D. Lundquist. 2018. "An Assessment of Differences in Gridded Precipitation Datasets in Complex Terrain." Journal of Hydrology 556 (January): 1205–19. https://doi.org/10.1016/j.jhydrol.2017.03.008.

Hereford, Richard, and Robert H. Webb. 1992. "Historic Variation of Warm-Season Rainfall, Southern Colorado Plateau, Southwestern U.S.A." Climatic Change 22 (3): 239–56. https://doi.org/10.1007/BF00143030.

Herman Jonathan D., Zeff Harrison B., Lamontagne Jonathan R., Reed Patrick M., and Characklis Gregory W. 2016. "Synthetic Drought Scenario Generation to Support Bottom-Up Water Supply Vulnerability Assessments." Journal of Water Resources Planning and Management 142 (11): 04016050. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000701.

Herweijer, Celine, Richard Seager, Edward R. Cook, and Julien Emile-Geay. 2007. "North American Droughts of the Last Millennium from a Gridded Network of Tree-Ring Data." Journal of Climate 20 (7): 1353–76. https://doi.org/10.1175/JCLI4042.1.

Hidalgo, Hugo G., Thomas C. Piechota, and John A. Dracup. 2000. "Alternative Principal Components Regression Procedures for Dendrohydrologic Reconstructions." Water Resources Research 36 (11): 3241–49.

Hidalgo, Hugo G. 2004. "Climate Precursors of Multidecadal Drought Variability in the Western United States." Water Resources Research 40 (12). https://doi.org/10.1029/2004WR003350.

Hidalgo, Hugo G., Michael D. Dettinger, and Daniel R. Cayan. 2008. "Downscaling with Constructed Analogues: Daily Precipitation and Temperature Fields Over the United States." California Energy Commission.

Hidalgo, Hugo G., and John A. Dracup. 2003. "ENSO and PDO Effects on Hydroclimatic Variability in the Upper Colorado River Basin." Journal of Hydrometeorology 4: 5–23.

Higgins, R. Wayne, H-K. Kim, and D. Unger. 2004. "Long-Lead Seasonal Temperature and Precipitation Prediction Using Tropical Pacific SST Consolidation Forecasts." Journal of Climate 17: 3398–3414. https://doi.org/10.1175/1520-0442(2004)017<3398:LSTAPP>2.0.CO;2.

Higgins, R. Wayne, Wei Shi, E. Yarosh, and R. Joyce. 2000. "Improved United States Precipitation Quality Control System and Analysis. NCEP/Climate Prediction Center ATLAS No. 7." U. S. DEPARTMENT OF COMMERCE National Oceanic and Atmospheric Administration National Weather Service. https://www.cpc.ncep.noaa.gov/products/outreach/research_papers/ncep_cpc_atlas/7/.

Hobbins, Michael T., and Justin L. Huntington. 2017. Evapotranspiration and Evaporative Demand, Chapter 42: Handbook of Applied Hydrology. Edited by V. P. Singh and Ven Te Chow. Second edition. New York: Mcgraw-Hill Education.

Hobbins, Michael T., Daniel McEvoy, and Christopher Hain. 2017. "Evapotranspiration, Evaporative Demand, and Drought." In Drought and Water Crises, by Donald Wilhite and Roger Pulwarty, 259–88. CRC Press. https://doi.org/10.1201/9781315265551-15.

Hobbins, Michael T., Andrew W. Wood, Daniel J. McEvoy, Justin L. Huntington, Charles Morton, Martha C. Anderson, and Christopher Hain. 2016. "The Evaporative Demand Drought Index. Part I: Linking Drought Evolution to Variations in Evaporative Demand." Journal of Hydrometeorology 17 (6): 1745–61. https://doi.org/10.1175/JHM-D-15-0121.1.

Hobbins, Michael T., Andrew W. Wood, David Streubel, and Kevin Werner. 2012. "What Drives the Variability of Evaporative Demand across the Conterminous United States?" Journal of Hydrometeorology 13 (4): 1195–1214. https://doi.org/10.1175/JHM-D-11-0101.1.

Hoerling, Martin P., Joseph J. Barsugli, B. Livneh, J. Eischeid, X. Quan, and A. Badger. 2019. "Causes for the Century-Long Decline in Colorado River Flow." Journal of Climate, August, JCLI-D-19-0207.1. https://doi.org/10.1175/JCLI-D-19-0207.1.

Hoerling, Martin P., Michael Dettinger, Klaus Wolter, Jeffrey J. Lukas, Jon Eischeid, Rama Nemani, Brant Liebmann, Kenneth E. Kunkel, and Arun Kumar. 2013. "Present Weather and Climate: Evolving Conditions." In Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment, edited by Gregg Garfin, Angela Jardine, Robert Merideth, Mary Black, and Sarah LeRoy, 74–100. Washington, DC: Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-484-0_5.

Hoerling, Martin P., Jon Eischeid, and Judith Perlwitz. 2010. "Regional Precipitation Trends: Distinguishing Natural Variability from Anthropogenic Forcing." Journal of Climate 23 (8): 2131–45. https://doi.org/10.1175/2009JCLI3420.1.

Hood, Eran, Mark Williams, and Don Cline. 1999. "Sublimation from a Seasonal Snowpack at a Continental, Mid-Latitude Alpine Site." Hydrological Processes 13 (12–13): 1781–97. https://doi.org/10.1002/(SICI)1099-1085(199909)13:12/13<1781::AID-HYP860>3.0.CO;2-C.

Huang, Chengcheng, Andrew J. Newman, Martyn P. Clark, Andrew W. Wood, and Xiaogu Zheng. 2017. “Evaluation of Snow Data Assimilation Using the Ensemble Kalman Filter for Seasonal Streamflow Prediction in the Western United States.” Hydrol. Earth Syst. Sci. 21 (1): 635–50. https://doi.org/10.5194/hess-21-635-2017.

Huang, Jin, Huug M. Van den Dool, and Anthony G. Barnston. 1996. “Long-Lead Seasonal Temperature Prediction Using Optimal Climate Normals.” Journal of Climate 9: 809–17. https://doi.org/10.1175/1520-0442(1996)009<0809:LLSTPU>2.0.CO;2.

Huang, Jin, Huug M. Van den Dool, and Konstantine P. Georgarakos. 1995. “Analysis of Model-Calculated Soil Moisture over the United States (1931–1993) and Applications to Long-Range Temperature Forecasts.” Journal of Climate. https://doi.org/10.1175/1520-0442(1996)009<1350:AOMCSM>2.0.CO;2.

Hubbard, K. G., X. Lin, and E. A. Walter-Shea. 2001. “The Effectiveness of the ASOS, MMTS, Gill, and CRS Air Temperature Radiation Shields*.” Journal of Atmospheric and Oceanic Technology 18 (6): 851–64. https://doi.org/10.1175/1520-0426(2001)018<0851:TEOTAM>2.0.CO;2.

Hudson, Debbie. 2017. “Ensemble Verification Metrics.” presented at the ECMWF Annual Seminar 2017, Reading, UK.

Hultstrand, Douglas M., and Steven R. Fassnacht. 2018. “The Sensitivity of Snowpack Sublimation Estimates to Instrument and Measurement Uncertainty Perturbed in a Monte Carlo Framework.” Frontiers of Earth Science 12 (4): 728–38. https://doi.org/10.1007/s11707-018-0721-0.

Hurrell, James W., M. M. Holland, P. R. Gent, S. Ghan, Jennifer E. Kay, and P. J. Kushner. 2013. “The Community Earth System Model,” 22.

Ikeda, Kyoko, Roy Rasmussen, Changhai Liu, David Gochis, David Yates, Fei Chen, Mukul Tewari, et al. 2010. “Simulation of Seasonal Snowfall over Colorado.” Atmospheric Research 97 (4): 462–77. https://doi.org/10.1016/j.atmosres.2010.04.010.

International Boundary and Water Commission. 2012. “Minute No. 319. Interim International Cooperative Measures in the Colorado River Basin Through 2017 and Extension of Minute 318 Cooperative Measures to Address the Continued Effects of the April 2010 Earthquake in the Mexicali Valley, Baja California.” https://www.ibwc.gov/Files/Minutes/Minute_319.pdf.

———. 2017. “Minute No. 323. Extension of Cooperative Measures and Adoption of a Binational Water Scarcity Contingency Plan in the Colorado River Basin.” https://www.ibwc.gov/Files/Minutes/Min323.pdf.

Interstate Council on Water Policy. 2012. “Colorado River Water Science Stakeholders’ Roundtable--A Meeing for USGS Cooperative Water Program Partners.” Pdf presented at the Colorado River Water Science Stakeholders’ Roundtable--A meeing for USGS Cooperative Water Program Partners, Salt Lake City, UT, February 8. https://water.usgs.gov/coop/meeting.book.01262012.pdf.

Iowa State University. n.d. “ASOS Network Quick Links.” Iowa Environmental Mesonet Networks. https://mesonet.agron.iastate.edu/ASOS/.

———. n.d. “AWOS Quick Links.” Iowa Environmental Mesonet Networks. https://mesonet.agron.iastate.edu/AWOS/.

———. n.d. “NWS COOP Quick Links.” Iowa Environmental Mesonet Networks. https://mesonet.agron.iastate.edu/COOP/.

———. n.d. “SCAN Network.” Iowa Environmental Mesonet Networks. https://mesonet.agron.iastate.edu/scan/.

Jana, Srijita, Balaji Rajagopalan, Michael A. Alexander, and Andrea J. Ray. 2018. “Understanding the Dominant Sources and Tracks of Moisture for Summer Rainfall in the Southwest United States.” Journal of Geophysical Research: Atmospheres 123 (10): 4850–70. https://doi.org/10.1029/2017JD027652.

Jensen, Marvin E., Avry Dotan, and Roland Sanford. 2005. “Penman-Monteith Estimates of Reservoir Evaporation.” In Impacts of Global Climate Change, 1–24. Anchorage, Alaska, United States: American Society of Civil Engineers. https://doi.org/10.1061/40792(173)548.

Johnson, Jennifer. 2014. “MODSIM versus RiverWare: A Comparative Analysis of Two River Reservoir Modeling Tools.” 2014.3669. US Bureau of Reclamation. https://www.usbr.gov/research/projects/download_product.cfm?id=1360.

Julander, Randall P., and Michael Bricco. 2006. “An Examination of External Influences Imbedded in the Historical Snow Data of Utah.” In Proceedings of the Western Snow Conference, 17. Utah State University.

Julander, Randall P., and Jordan A. Clayton. 2018. “Determining the Proportion of Streamflow That Is Generated by Cold Season Processes versus Summer Rainfall in Utah, USA.” Journal of Hydrology: Regional Studies 17 (June): 36–46. https://doi.org/10.1016/j.ejrh.2018.04.005.

Kain, John S., Stephen M. Goss, and Michael E. Baldwin. 2000. “The Melting Effect as a Factor in Precipitation-Type Forecasting.” Weather and Forecasting 15 (6): 700–714. https://doi.org/10.1175/1520-0434(2000)015<0700:TMEAAF>2.0.CO;2.

Kalnay, Eugenia, Masao Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, et al. 1996. “The NCEP/NCAR 40-Year Reanalysis Project.” Bulletin of the American Meteorological Society 77 (3): 437–71. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kapnick, Sarah B., Xiaosong Yang, Gabriel A. Vecchi, Thomas L. Delworth, Rich Gudgel, Sergey Malyshev, P. C. D. Milly, Elena Shevliakova, Seth Underwood, and Steven A. Margulis. 2018. “Potential for Western US Seasonal Snowpack Prediction.” Proceedings of the National Academy of Sciences 115 (6): 1180–85. https://doi.org/10.1073/pnas.1716760115.

Karl, Thomas R., H. F. Diaz, and George Kukla. 1988. “Urbanization: Its Detection and Effect in the United States Climate Record.” Journal of Climate 1: 1099–1123.

Karl, Thomas R., Claude N. Williams, Pamela J. Young, and Wayne M. Wendland. 1986. “A Model to Estimate the Time of Observation Bias Associated with Monthly Mean, Maximum, Minimum, and Mean Temperatures for the United States.” Journal of Climate and Applied Meteorology 25: 145–60.

Kay, Jennifer E., C. Deser, A. Phillips, A. Mai, C. Hannay, G. Strand, J. M. Arblaster, et al. 2015. “The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability.” Bulletin of the American Meteorological Society 96 (8): 1333–49. https://doi.org/10.1175/BAMS-D-13-00255.1.

Kendall, Donald R., and John A. Dracup. 1991. “A Comparison of Index-Sequential and AR(1) Generated Hydrologic Sequences.” Journal of Hydrology 122 (1): 335–52. https://doi.org/10.1016/0022-1694(91)90187-M.

Kenney, Douglas S., Christopher Goemans, Roberta Klein, Jessica Lowrey, and Kevin Reidy. 2008. “Residential Water Demand Management: Lessons from Aurora, Colorado.” JAWRA Journal of the American Water Resources Association 44 (1): 192–207. https://doi.org/10.1111/j.1752-1688.2007.00147.x.

Khaliq, M. N., T. B. M. J. Ouarda, J. -C. Ondo, P. Gachon, and B. Bobée. 2006. “Frequency Analysis of a Sequence of Dependent and/or Non-Stationary Hydro-Meteorological Observations: A Review.” Journal of Hydrology 329 (3): 534–52. https://doi.org/10.1016/j.jhydrol.2006.03.004.

Kiang, Julie E., Chris Gazoorian, Hilary McMillan, Gemma Coxon, Jérôme Le Coz, Ida K. Westerberg, Arnaud Belleville, et al. 2018. “A Comparison of Methods for Streamflow Uncertainty Estimation.” Water Resources Research 54 (10): 7149–76. https://doi.org/10.1029/2018WR022708.

Kiang, Julie E., David W. Stewart, Stacey A. Archfield, Emily B. Osborne, and Ken Eng. 2013. "A National Streamflow Network Gap Analysis." Scientific Investigations Report 2013–5013. Scientific Investigations Report. U.S. Geological Survey. https://pubs.usgs.gov/sir/2013/5013/pdf/sir2013-5013.pdf.

Kidston, Joseph, Adam A. Scaife, Steven C. Hardiman, Daniel M. Mitchell, Neal Butchart, Mark P. Baldwin, and Lesley J. Gray. 2015. "Stratospheric Influence on Tropospheric Jet Streams, Storm Tracks and Surface Weather." Nature Geoscience 8 (6): 433–40. https://doi.org/10.1038/ngeo2424.

Kirtman, Ben P., Dughong Min, Johnna M. Infanti, James L. Kinter, Daniel A. Paolino, Qin Zhang, Huug M. Van den Dool, et al. 2014. "The North American Multimodel Ensemble: Phase-1 Seasonal-to-Interannual Prediction; Phase-2 toward Developing Intraseasonal Prediction." Bulletin of the American Meteorological Society 95 (4): 585–601. https://doi.org/10.1175/BAMS-D-12-00050.1.

Klotzbach, Philip J. 2014. "The Madden–Julian Oscillation's Impacts on Worldwide Tropical Cyclone Activity." Journal of Climate 27 (6): 2317–30. https://doi.org/10.1175/JCLI-D-13-00483.1.

Knaff, John A., and Christopher W. Landsea. 1997. "An El Niño Southern Oscillation CLImatology and PERsistence (CLIPER) Forecasting Scheme." Weather and Forecasting 12 (3): 633–52. https://doi.org/10.1175/1520-0434(1997)012<0633:AENOSO>2.0.CO;2 Cite this publication.

Knowles, Noah, Michael D. Dettinger, and Daniel R. Cayan. 2006. "Trends in Snowfall versus Rainfall in the Western United States." Journal of Climate 19 (18): 4545–59. https://doi.org/10.1175/JCLI3850.1.

Knutti, Reto. 2010. "The End of Model Democracy?: An Editorial Comment." Climatic Change 102 (3–4): 395–404. https://doi.org/10.1007/s10584-010-9800-2.

Knutti, Reto, Reinhard Furrer, Claudia Tebaldi, Jan Cermak, and Gerald A. Meehl. 2010. "Challenges in Combining Projections from Multiple Climate Models." Journal of Climate 23 (10): 2739–58. https://doi.org/10.1175/2009JCLI3361.1.

Knutti, Reto, David Masson, and Andrew Gettelman. 2013. "Climate Model Genealogy: Generation CMIP5 and How We Got There." Geophysical Research Letters 40 (6): 1194–99. https://doi.org/10.1002/grl.50256.

Koren, Victor, Michael Smith, and Qingyun Duan. 2003. "Use of a Priori Parameter Estimates in the Derivation of Spatially Consistent Parameter Sets of Rainfall-Runoff Models." In Calibration of Watershed Models, 239–54. American Geophysical Union (AGU). https://doi.org/10.1002/9781118665671.ch18.

Koster, Randal D., S. P. P. Mahanama, T. J. Yamada, Gianpaolo Balsamo, A. A. Berg, M. Boisserie, P. A. Dirmeyer, et al. 2011. "The Second Phase of the Global Land–Atmosphere Coupling Experiment: Soil Moisture Contributions to Subseasonal Forecast Skill." Journal of Hydrometeorology 12 (5): 805–22. https://doi.org/10.1175/2011JHM1365.1.

Kuhn, Eric, and John Fleck. 2019. Science Be Dammed. Tucson: University of Arizona Press.

Kuiper, Dana, Rose Loehr, Maggie Dunklee, Laurel Grimsted, and Tony Tolsdorf. 2014. "Chapter 6. Data Management." In Part 622 Snow Survey and Water Supply Forecasting National Engineering Handbook. USDA Natural Resources Conservation Service.

Kumar, Sanjiv, Matthew Newman, Yan Wang, and Ben Livneh. 2019. "Potential Reemergence of Seasonal Soil Moisture Anomalies in North America." Journal of Climate 32 (10): 2707–34. https://doi.org/10.1175/JCLI-D-18-0540.1.

Kumar, Sujay V., Benjamin F. Zaitchik, Christa D. Peters-Lidard, Matthew Rodell, Rolf Reichle, Bailing Li, Michael Jasinski, et al. 2016. "Assimilation of Gridded GRACE Terrestrial Water Storage Estimates in the North American Land Data Assimilation System." Journal of Hydrometeorology 17 (7): 1951–72. https://doi.org/10.1175/JHM-D-15-0157.1.

Labadie, John W., Fontane Darrell G., Tabios Guillermo Q., and Chou Nine Fang. 1987. "Stochastic Analysis of Dependable Hydropower Capacity." Journal of Water Resources Planning and Management 113 (3): 422–37. https://doi.org/10.1061/(ASCE)0733-9496(1987)113:3(422).

Lall, Upmanu. 1995. "Recent Advances in Nonparametric Function Estimation: Hydrologic Applications." Reviews of Geophysics 33 (S2): 1093–1102. https://doi.org/10.1029/95RG00343.

Lall, Upmanu, and Ashish Sharma. 1996. "A Nearest Neighbor Bootstrap For Resampling Hydrologic Time Series." Water Resources Research 32 (3): 679–93. https://doi.org/10.1029/95WR02966.

Lamb, Kenneth W. 2010. "Improving Ensemble Streamflow Prediction Using Interdecadal/Interannual Climate Variability." UNLV Theses, Dissertations, Professional Papers, and Capstones, December, 718.

Lane, William L., and Donald K. Frevert. 1988. "Applied Stochastic Techniques: LAST Computer Package : User Manual." Manual. Denver, Colorado: Division of Planning Technical Services, Engineering and Research Center, Bureau of Reclamation, U.S. Dept. of the Interior.

Langousis, Andreas, and Vassilios Kaleris. 2014. "Statistical Framework to Simulate Daily Rainfall Series Conditional on Upper-Air Predictor Variables." Water Resources Research 50 (5): 3907–32. https://doi.org/10.1002/2013WR014936.

Lanzante, John R., Keith W. Dixon, Mary Jo Nath, Carolyn E. Whitlock, and Dennis Adams-Smith. 2018. "Some Pitfalls in Statistical Downscaling of Future Climate." Bulletin of the American Meteorological Society 99 (4): 791–803. https://doi.org/10.1175/BAMS-D-17-0046.1.

Lareau, Neil P., and John D. Horel. 2012. "The Climatology of Synoptic-Scale Ascent over Western North America: A Perspective on Storm Tracks." Monthly Weather Review 140 (6): 1761–78. https://doi.org/10.1175/MWR-D-11-00203.1.

Lee, Taesam S., Jose D. Salas, J. Keedy, D. Frevert, and T. Fulp. 2007. "Stochastic Modeling and Simulation of the Colorado River Flows." In World Environmental and Water Resources Congress 2007, 1–10. Tampa, Florida, United States: American Society of Civil Engineers. https://doi.org/10.1061/40927(243)423.

Lee, Taesam S., and Jose D. Salas. 2006. "Record Extension of Monthly Flows for the Colorado River System." US Bureau of Reclamation. https://www.usbr.gov/lc/region/g4000/NaturalFlow/Final.RecordExtensionReport.2006.pdf.

———. 2011. "Copula-Based Stochastic Simulation of Hydrological Data Applied to Nile River Flows." Hydrology Research 42 (4): 318–30. https://doi.org/10.2166/nh.2011.085.

Leeper, Ronald D., Jared Rennie, and Michael A. Palecki. 2015. "Observational Perspectives from U.S. Climate Reference Network (USCRN) and Cooperative Observer Program (COOP) Network: Temperature and Precipitation Comparison." Journal of Atmospheric and Oceanic Technology 32 (4): 703–21. https://doi.org/10.1175/JTECH-D-14-00172.1.

Lehner, Flavio, Clara Deser, Isla R. Simpson, and Laurent Terray. 2018. "Attributing the U.S. Southwest's Recent Shift Into Drier Conditions." Geophysical Research Letters 45 (12): 6251–61. https://doi.org/10.1029/2018GL078312.

Lehner, Flavio, Andrew W. Wood, J. A. Vano, D. M. Lawrence, Martyn P. Clark, and Justin S. Mankin. 2019. "The Potential to Reduce Uncertainty in Regional Runoff Projections from Climate Models." Nature Climate Change 9: 926–33. https://doi.org/10.1038/s41558-019-0639-x.

Lehner, Flavio, Andrew W. Wood, Dagmar Llewellyn, Douglas B. Blatchford, Angus G. Goodbody, and Florian Pappenberger. 2017. "Mitigating the Impacts of Climate Nonstationarity on Seasonal Streamflow Predictability in the U.S. Southwest." Geophysical Research Letters 44 (24): 12,208-12,217. https://doi.org/10.1002/2017GL076043.

Lenaerts, Jan T. M., Brooke Medley, Michiel R. van den Broeke, and Bert Wouters. 2019. "Observing and Modeling Ice Sheet Surface Mass Balance." Reviews of Geophysics 57 (2): 376–420. https://doi.org/10.1029/2018RG000622.

Letcher, Theodore W., and Justin R. Minder. 2015. “Characterization of the Simulated Regional Snow Albedo Feedback Using a Regional Climate Model over Complex Terrain.” Journal of Climate 28 (19): 7576–95. https://doi.org/10.1175/JCLI-D-15-0166.1.

Leung, L. Ruby, Ying-Hwa Kuo, and Joe Tribbia. 2006. “Research Needs and Directions of Regional Climate Modeling Using WRF and CCSM.” Bulletin of the American Meteorological Society 87 (12): 1747–52. https://doi.org/10.1175/BAMS-87-12-1747.

Li, Dongyue, Melissa L. Wrzesien, Michael Durand, Jennifer Adam, and Dennis P. Lettenmaier. 2017. “How Much Runoff Originates as Snow in the Western United States, and How Will That Change in the Future?” Geophysical Research Letters 44 (12): 6163–72. https://doi.org/10.1002/2017GL073551.

Li, Haibin, Justin Sheffield, and Eric F. Wood. 2010. “Bias Correction of Monthly Precipitation and Temperature Fields from Intergovernmental Panel on Climate Change AR4 Models Using Equidistant Quantile Matching.” Journal of Geophysical Research 115 (D10): D10101. https://doi.org/10.1029/2009JD012882.

Liang, Xu, Dennis P. Lettenmaier, Eric F. Wood, and Stephen J. Burges. 1994. “A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models.” Journal of Geophysical Research: Atmospheres 99 (D7): 14415–28. https://doi.org/10.1029/94JD00483.

Lin, X., and K. G. Hubbard. 2004. “Sensor and Electronic Biases/Errors in Air Temperature Measurements in Common Weather Station Networks*.” Journal of Atmospheric and Oceanic Technology 21 (7): 1025–32. https://doi.org/10.1175/1520-0426(2004)021<1025:SAEEIA>2.0.CO;2.

Linacre, Edward. 1992. Climate Data and Resources: A Reference and Guide.

Liston, Glen E., and Kelly Elder. 2006. “A Distributed Snow-Evolution Modeling System (SnowModel).” Journal of Hydrometeorology 7 (6): 1259–76. https://doi.org/10.1175/JHM548.1.

Liu, Changhai, Kyoko Ikeda, Roy Rasmussen, Mike Barlage, Andrew J. Newman, Andreas F. Prein, Fei Chen, et al. 2017. “Continental-Scale Convection-Permitting Modeling of the Current and Future Climate of North America.” Climate Dynamics 49 (1–2): 71–95. https://doi.org/10.1007/s00382-016-3327-9.

Liu, Yuqiong, A. H. Weerts, Martyn P. Clark, H.-J. Hendricks Franssen, S. Kumar, H. Moradkhani, D.-J. Seo, et al. 2012. “Advancing Data Assimilation in Operational Hydrologic Forecasting: Progresses, Challenges, and Emerging Opportunities.” Hydrology and Earth System Sciences 16 (10): 3863–87. https://doi.org/10.5194/hess-16-3863-2012.

Livezey, Robert E., and Marina M. Timofeyeva. 2008. “The First Decade of Long-Lead U.S. Seasonal Forecasts: Insights from a Skill Analysis.” Bulletin of the American Meteorological Society 89 (6): 843–54. https://doi.org/10.1175/2008BAMS2488.1.

Livneh, Ben. n.d. “Data Sets: Daily Observational Hydrometeorology Data Set: CONUS Extent with Canadian Extent of the Columbia River Basin.” Water and Climate Research Group. https://ciresgroups.colorado.edu/livneh/data/.

———. n.d. “Data Sets: Daily Observational Hydrometeorology Data Set: North American Extent.” Water and Climate Research Group. https://ciresgroups.colorado.edu/livneh/data/.

Livneh, Ben, Andrew M. Badger, and Jeffrey J. Lukas. 2017. “Assessing the Robustness of Snow-Based Drought Indicators in the Upper Colorado River Basin under Future Climate Change.” In World Environmental and Water Resources Congress 2017, 511–25. Sacramento, California: American Society of Civil Engineers. https://doi.org/10.1061/9780784480618.051.

Livneh, Ben, Theodore J. Bohn, David W. Pierce, Francisco Munoz-Arriola, Bart Nijssen, Russell Vose, Daniel R. Cayan, and Levi Brekke. 2015. “A Spatially Comprehensive, Hydrometeorological Data Set for Mexico, the U.S., and Southern Canada 1950–2013.” Scientific Data 2 (August): 150042. https://doi.org/10.1038/sdata.2015.42.

Livneh, Ben, Eric A. Rosenberg, Chiyu Lin, Bart Nijssen, Vimal Mishra, Kostas M. Andreadis, Edwin P. Maurer, and Dennis P. Lettenmaier. 2013. "A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions." Journal of Climate 26 (23): 9384–92. https://doi.org/10.1175/JCLI-D-12-00508.1.

Loucks, Daniel P., and Eelco van Beek. 2017. Water Resource Systems Planning and Management. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-44234-1.

Lukas, Jeffrey J., Joseph J. Barsugli, Nolan J. Doesken, Imtiaz Rangwala, and Klaus Wolter. 2014. "Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation." Western Water Assessment, University of Colorado Boulder. https://wwa.colorado.edu/climate/co2014report/Climate_Change_CO_Report_2014_FINAL.pdf.

Lukas, Jeffrey J., Elizabeth McNie, Tim Bardsley, Jeffrey S. Deems, and Noah Molotch. 2016. "Snowpack Monitoring for Streamflow Forecasting and Drought Planning." Western Water Assesseement.

Lukas, Jeffrey J., Lisa Wade, and Balaji Rajagopalan. 2013. "Paleohydrology of the Lower Colorado River Basin."

Lundquist, Jessica D., Mimi Hughes, Brian Henn, Ethan D. Gutmann, Ben Livneh, Jeff Dozier, and Paul Neiman. 2015. "High-Elevation Precipitation Patterns: Using Snow Measurements to Assess Daily Gridded Datasets across the Sierra Nevada, California." Journal of Hydrometeorology 16 (4): 1773–92. https://doi.org/10.1175/JHM-D-15-0019.1.

Luo, Lifeng, and Eric F. Wood. 2008. "Use of Bayesian Merging Techniques in a Multimodel Seasonal Hydrologic Ensemble Prediction System for the Eastern United States." Journal of Hydrometeorology 9 (5): 866–84. https://doi.org/10.1175/2008JHM980.1.

Lute, A. C., John T. Abatzoglou, and Katherine C. Hegewisch. 2015. "Projected Changes in Snowfall Extremes and Interannual Variability of Snowfall in the Western United States." Water Resources Research 51 (2): 960–72. https://doi.org/10.1002/2014WR016267.

Lynker. 2019. "CRAM Water Resources Modeling Tool." https://www.lynker.com/wp-content/uploads/CRAM-Model-Lynker.pdf.

Ma, Chenchen. 2017. "Evaluating and Correcting Sensor Change Artifacts in the SNOTEL Temperature Records, Southern Rocky Mountains, Colorado." Ft. Collins, CO: Colorado State University.

MacDonald, Glen M., and Roslyn A. Case. 2005. "Variations in the Pacific Decadal Oscillation over the Past Millennium." Geophysical Research Letters 32 (8). https://doi.org/10.1029/2005GL022478.

MacDonald, Glen M., and Abbie H. Tingstad. 2007. "Recent and Multicentennial Precipitation Variability and Drought Occurrence in the Uinta Mountains Region, Utah." Arctic, Antarctic, and Alpine Research 39 (4): 549–55. https://doi.org/10.1657/1523-0430(06-070)[MACDONALD]2.0.CO;2.

Mahoney, Kelly, Michael Alexander, James D. Scott, and Joseph J. Barsugli. 2013. "High-Resolution Downscaled Simulations of Warm-Season Extreme Precipitation Events in the Colorado Front Range under Past and Future Climates." Journal of Climate 26 (21): 8671–89. https://doi.org/10.1175/JCLI-D-12-00744.1.

Maloney, Eric D., and Dennis L. Hartmann. 2000. "Modulation of Eastern North Pacific Hurricanes by the Madden–Julian Oscillation." Journal of Climate 13: 10.

Mamalakis, Antonios, Jin-Yi Yu, James T. Randerson, Amir AghaKouchak, and Efi Foufoula-Georgiou. 2018. "A New Interhemispheric Teleconnection Increases Predictability of Winter Precipitation in Southwestern US." Nature Communications 9 (1). https://doi.org/10.1038/s41467-018-04722-7.

Mantua, Nathan J., Michael Dettinger, Thomas C. Pagano, and Pedro Restrepo. 2008. "A Description and Evaluation of Hydrologic and Climate Forecast and Data Products That Support Decision-Making for Water Resource Managers." Asheville, NC. https://pdfs.semanticscholar.org/ad74/f7701476a309e366190b246936fe0e150a7d.pdf?_ga=2.174838242.1797202885.1563210564-120100695.1562772778.

Mantua, Nathan J., Steven R. Hare, Yuan Zhang, John M. Wallace, and Robert C. Francis. 1997. "A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production." Bulletin of the American Meteorological Society 78 (6): 1069–79. https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.

Maraun, Douglas. 2016. "Bias Correcting Climate Change Simulations - a Critical Review." Current Climate Change Reports 2 (4): 211–20. https://doi.org/10.1007/s40641-016-0050-x.

Maraun, Douglas, Theodore G. Shepherd, Martin Widmann, Giuseppe Zappa, Daniel Walton, José M. Gutiérrez, Stefan Hagemann, et al. 2017. "Towards Process-Informed Bias Correction of Climate Change Simulations." Nature Climate Change 7 (11): 764–73. https://doi.org/10.1038/nclimate3418.

Marco, J. B., R. Harboe, and J. D. Salas. 1993. Stochastic Hydrology and Its Use in Water Resources Systems Simulation and Optimization. Vol. 237. NATO ASI Series, E. Kluwer Academic Publishers.

Mariotti, Annarita, Cory Baggett, Elizabeth A. Barnes, Emily Becker, Amy Butler, Dan C. Collins, Paul A. Dirmeyer, et al. 2020. "Windows of Opportunity for Skillful Forecasts Subseasonal to Seasonal and Beyond." Bulletin of the American Meteorological Society, January, BAMS-D-18-0326.1. https://doi.org/10.1175/BAMS-D-18-0326.1.

Mariotti, Annarita, Paolo M. Ruti, and Michel Rixen. 2018. "Progress in Subseasonal to Seasonal Prediction through a Joint Weather and Climate Community Effort." Npj Climate and Atmospheric Science 1 (1). https://doi.org/10.1038/s41612-018-0014-z.

Matott, L. Shawn, Beth Hymiak, Camden Reslink, Christine Baxter, and Shirmin Aziz. 2013. "Telescoping Strategies for Improved Parameter Estimation of Environmental Simulation Models." Computers & Geosciences 60 (October): 156–67. https://doi.org/10.1016/j.cageo.2013.07.023.

Maurer, Edwin P., and David W. Pierce. 2014. "Bias Correction Can Modify Climate Model Simulated Precipitation Changes without Adverse Effect on the Ensemble Mean." Hydrology and Earth System Sciences 18 (3): 915–25. https://doi.org/10.5194/hess-18-915-2014.

Maurer, Edwin P., Andrew W. Wood, Jennifer C. Adam, Dennis P. Lettenmaier, and Bart Nijssen. 2002. "A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States." Journal of Climate 15 (22): 3237–51. https://doi.org/10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2.

Maxwell, Reed M., Laura E. Condon, Stefan J. Kollet, Kate Maher, Roy Haggerty, and Mary Michael Forrester. 2016. "The Imprint of Climate and Geology on the Residence Times of Groundwater." Geophysical Research Letters 43 (2): 701–8. https://doi.org/10.1002/2015GL066916.

Maxwell, Reed M., and Norman L. Miller. 2005. "Development of a Coupled Land Surface and Groundwater Model." Journal of Hydrometeorology 6 (3): 233–47. https://doi.org/10.1175/JHM422.1.

McAfee, Stephanie A. 2014. "Consistency and the Lack Thereof in Pacific Decadal Oscillation Impacts on North American Winter Climate." Journal of Climate 27 (19): 7410–31. https://doi.org/10.1175/JCLI-D-14-00143.1.

McAfee, Stephanie A., Galina Guentchev, and Jon Eischeid. 2014. "Reconciling Precipitation Trends in Alaska: 2. Gridded Data Analyses." Journal of Geophysical Research: Atmospheres 119 (24): 13,820-13,837. https://doi.org/10.1002/2014JD022461.

McAfee, Stephanie A., Gregory J. McCabe, Stephen T. Gray, and Gregory T. Pederson. 2019. "Changing Station Coverage Impacts Temperature Trends in the Upper Colorado River Basin." International Journal of Climatology 39 (3): 1517–38. https://doi.org/10.1002/joc.5898.

McAfee, Stephanie A., Joellen L. Russell, and Paul J. Goodman. 2011. "Evaluating IPCC AR4 Cool-Season Precipitation Simulations and Projections for Impacts Assessment over North America." Climate Dynamics 37 (11–12): 2271–87. https://doi.org/10.1007/s00382-011-1136-8.

McCabe, Gregory J., and Steven L. Markstrom. 2007. "A Monthly Water-Balance Model Driven By a Graphical User Interface." Open-File Report 2007–1088. U.S. Geological Survey.

McCabe, Gregory J., Michael A. Palecki, and Julio L. Betancourt. 2004. "Pacific and Atlantic Ocean Influences on Multidecadal Drought Frequency in the United States." Proceedings of the National Academy of Sciences 101 (12): 4136–41. https://doi.org/10.1073/pnas.0306738101.

McCabe, Gregory J., and David M. Wolock. 2007. "Warming May Create Substantial Water Supply Shortages in the Colorado River Basin." Geophysical Research Letters 34 (22). https://doi.org/10.1029/2007GL031764.

———. 2011. "Independent Effects of Temperature and Precipitation on Modeled Runoff in the Conterminous United States." Water Resources Research 47 (11). https://doi.org/10.1029/2011WR010630.

———. 2019. "Hydroclimatology of the Mississippi River Basin." JAWRA Journal of the American Water Resources Association 55 (4): 1053–64. https://doi.org/10.1111/1752-1688.12749.

McCabe, Gregory J., David M. Wolock, Gregory T. Pederson, Connie A. Woodhouse, and Stephanie A. McAfee. 2017. "Evidence That Recent Warming Is Reducing Upper Colorado River Flows." Earth Interactions 21 (10): 1–14. https://doi.org/10.1175/EI-D-17-0007.1.

McGuire, Marketa, Andrew W. Wood, Alan F. Hamlet, and Dennis P. Lettenmaier. 2006. "Use of Satellite Data for Streamflow and Reservoir Storage Forecasts in the Snake River Basin." Journal of Water Resources Planning and Management 132 (2): 97–110. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:2(97).

McKinnon, Karen A., Andrew Poppick, Etienne Dunn-Sigouin, and Clara Deser. 2017. "An 'Observational Large Ensemble' to Compare Observed and Modeled Temperature Trend Uncertainty Due to Internal Variability." Journal of Climate 30 (19): 7585–98. https://doi.org/10.1175/JCLI-D-16-0905.1.

McMahon, Thomas A., Richard M. Vogel, Murray C. Peel, and Geoffrey G.S. Pegram. 2007. "Global Streamflows – Part 1: Characteristics of Annual Streamflows." Journal of Hydrology 347 (3–4): 243–59. https://doi.org/10.1016/j.jhydrol.2007.09.002.

McMillan, Hilary, Tobias Krueger, and Jim Freer. 2012. "Benchmarking Observational Uncertainties for Hydrology: Rainfall, River Discharge and Water Quality." Hydrological Processes 26 (26): 4078–4111. https://doi.org/10.1002/hyp.9384.

McMillan, Hilary, Jan Seibert, Asgeir Petersen-Overleir, Michel Lang, Paul White, Ton Snelder, Kit Rutherford, Tobias Krueger, Robert Mason, and Julie Kiang. 2017. "How Uncertainty Analysis of Streamflow Data Can Reduce Costs and Promote Robust Decisions in Water Management Applications." Water Resources Research 53 (7): 5220–28. https://doi.org/10.1002/2016WR020328.

Mearns, Linda, S. Sain, L. R. Leung, M. S. Bukovsky, S. McGinnis, S. Biner, D. Caya, et al. 2013. "Climate Change Projections of the North American Regional Climate Change Assessment Program (NARCCAP)." Climatic Change 120 (4): 965–75. https://doi.org/10.1007/s10584-013-0831-3.

Mearns, Linda, Seth McGinnis, Daniel Korytina, Raymond Arritt, Sébastien Biner, Melissa Bukovsky, Hsin-I Chang, et al. 2017. "The NA-CORDEX Dataset." UCAR/NCAR. https://doi.org/10.5065/d6sj1jch.

Meko, David M., Charles W. Stockton, and W. R. Boggess. 1995. "The Tree-Ring Record of Severe Sustained Drought." Journal of the American Water Resources Association 31 (5): 789–801. https://doi.org/10.1111/j.1752-1688.1995.tb03401.x.

Meko, David M., and Connie A. Woodhouse. 2011. "Dendroclimatology, Dendrohydrology, and Water Resources Management." In Tree Rings and Climate: Progress and Prospects. Springer.

Meko, David M., Connie A. Woodhouse, Christopher A. Baisan, Troy Knight, Jeffrey J. Lukas, Malcolm K. Hughes, and Matthew W. Salzer. 2007. "Medieval Drought in the Upper Colorado River Basin." Geophysical Research Letters 34 (10). https://doi.org/10.1029/2007GL029988.

Meko, David M., Connie A. Woodhouse, and E.R. Bigio. 2017. "Final Report: Southern California Tree-Ring Study." California Department of Water Resources. https://data.ca.gov/dataset/paleo-dendrochronological-tree-ring-hyrdoclimatic-reconstructions-northern-and-southern-14.

Meko, David M., Connie A. Woodhouse, and K. Morino. 2012. "Dendrochronology and Links to Streamflow." Journal of Hydrology 412–413 (January): 200–209. https://doi.org/10.1016/j.jhydrol.2010.11.041.

Mendoza, Pablo A., Martyn P. Clark, Michael Barlage, Balaji Rajagopalan, Luis Samaniego, Gab Abramowitz, and Hoshin Vijai Gupta. 2015. "Are We Unnecessarily Constraining the Agility of Complex Process-based Models?" Water Resources Research 51 (1): 716–28.

Mendoza, Pablo A., Andrew W. Wood, Elizabeth Clark, Eric Rothwell, Martyn P. Clark, Bart Nijssen, Levi D. Brekke, and Jeffrey R. Arnold. 2017. "An Intercomparison of Approaches for Improving Operational Seasonal Streamflow Forecasts." Hydrology and Earth System Sciences 21 (7): 3915–35. https://doi.org/10.5194/hess-21-3915-2017.

Menne, Matthew J., Imke Durre, Russell S. Vose, Byron E. Gleason, and Tamara G. Houston. 2012. "An Overview of the Global Historical Climatology Network-Daily Database." Journal of Atmospheric and Oceanic Technology 29 (7): 897–910. https://doi.org/10.1175/JTECH-D-11-00103.1.

Menne, Matthew J., and Claude N. Williams. 2009. "Homogenization of Temperature Series via Pairwise Comparisons." Journal of Climate 22 (7): 1700–1717. https://doi.org/10.1175/2008JCLI2263.1.

Menne, Matthew J., Claude N. Williams, and Russell S. Vose. 2009. "The U.S. Historical Climatology Network Monthly Temperature Data, Version 2." Bulletin of the American Meteorological Society 90 (7): 993–1008. https://doi.org/10.1175/2008BAMS2613.1.

Mesinger, Fedor, Geoff DiMego, Eugenia Kalnay, Kenneth Mitchell, Perry C. Shafran, Wesley Ebisuzaki, Dušan Jović, et al. 2006. "North American Regional Reanalysis." Bulletin of the American Meteorological Society 87 (3): 343–60. https://doi.org/10.1175/BAMS-87-3-343.

Michaelsen, Joel. 1987. "Cross-Validation in Statistical Climate Forecast Models." Journal of Climate and Applied Meteorology 26: 1589–1600.

Michaelsen, Joel, H. A. Loaiciga, L. Haston, and S. Garver. 1990. "Estimating Drought Probabilities in California Using Tree Rings. California Department of Water Resources Report B- 57105." University of California, Santa Barbara CA.

Miller, Matthew P., Susan G. Buto, David D. Susong, and Christine A. Rumsey. 2016. "The Importance of Base Flow in Sustaining Surface Water Flow in the Upper Colorado River Basin." Water Resources Research 52 (5): 3547–62. https://doi.org/10.1002/2015WR017963.

Miller, W. Paul, R. Alan Butler, Thomas Piechota, James Prairie, Katrina Grantz, and Gina DeRosa. 2012. "Water Management Decisions Using Multiple Hydrologic Models within the San Juan River Basin under Changing Climate Conditions." Journal of Water Resources Planning and Management 138 (5): 412–20. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000237.

Miller, W. Paul, Gina M. DeRosa, Subhrendu Gangopadhyay, and Juan B. Valdés. 2013. "Predicting Regime Shifts in Flow of the Gunnison River under Changing Climate Conditions: Regime Shifts Over the Gunnison River Basin." Water Resources Research 49 (5): 2966–74. https://doi.org/10.1002/wrcr.20215.

Miller, W. Paul, Thomas Piechota, Subhrendu Gangopadhyay, and Tom Pruitt. 2011. "Development of Streamflow Projections Under Changing Climate Conditions Over Colorado River Basin Headwaters." Hydrol. Earth Syst. Sci., 21.

Milly, P. C. D., Julio Betancourt, Malin Falkenmark, Robert M. Hirsch, Zbigniew W. Kundzewicz, Dennis P. Lettenmaier, and Ronald J. Stouffer. 2008. "Stationarity Is Dead: Whither Water Management?" Science 319 (5863): 573–74. https://doi.org/10.1126/science.1151915.

Milly, P. C. D., Julio Betancourt, Malin Falkenmark, Robert M. Hirsch, Zbigniew W. Kundzewicz, Dennis P. Lettenmaier, Ronald J. Stouffer, Michael D. Dettinger, and Valentina Krysanova. 2015. "On Critiques of 'Stationarity Is Dead: Whither Water Management?'" Water Resources Research 51 (9): 7785–89. https://doi.org/10.1002/2015WR017408.

Milly, P. C. D., and K. A. Dunne. 2020. "Colorado River Flow Dwindles as Warming-Driven Loss of Reflective Snow Energizes Evaporation." Science, February. https://doi.org/10.1126/science.aay9187.

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia. 2005. "Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate." Nature 438 (7066): 347–50. https://doi.org/10.1038/nature04312.

Mitchell, Kenneth E. 2004. "The Multi-Institution North American Land Data Assimilation System (NLDAS): Utilizing Multiple GCIP Products and Partners in a Continental Distributed Hydrological Modeling System." Journal of Geophysical Research 109 (D7). https://doi.org/10.1029/2003JD003823.

Mizukami, Naoki, Martyn P. Clark, Ethan D. Gutmann, Pablo A. Mendoza, Andrew J. Newman, Bart Nijssen, Ben Livneh, Lauren E. Hay, Jeffrey R. Arnold, and Levi D. Brekke. 2016. "Implications of the Methodological Choices for Hydrologic Portrayals of Climate Change over the Contiguous United States: Statistically Downscaled Forcing Data and Hydrologic Models." Journal of Hydrometeorology 17 (1): 73–98. https://doi.org/10.1175/JHM-D-14-0187.1.

Mizukami, Naoki, Martyn P. Clark, Andrew J. Newman, Andrew W. Wood, Ethan D. Gutmann, Bart Nijssen, Oldrich Rakovec, and Luis Samaniego. 2017. "Towards Seamless Large-Domain Parameter Estimation for Hydrologic Models." Water Resources Research 53 (9): 8020–40. https://doi.org/10.1002/2017WR020401.

Mizukami, Naoki, Martyn P. Clark, K. Sampson, B. Nijssen, Yixin Mao, Hilary McMillan, R. J. Viger, et al. 2016. "MizuRoute Version 1: A River Network Routing Tool for a Continental Domain Water Resources Applications." Geoscientific Model Development 9 (6): 2223–38.

Mo, Kingtse C. 2003. "Ensemble Canonical Correlation Prediction of Surface Temperature over the United States." Journal of Climate 16 (11): 1665–83. https://doi.org/10.1175/1520-0442(2003)016<1665:ECCPOS>2.0.CO;2.

Mo, Kingtse C., and Dennis P. Lettenmaier. 2014. "Hydrologic Prediction over the Conterminous United States Using the National Multi-Model Ensemble." Journal of Hydrometeorology 15 (4): 1457–72. https://doi.org/10.1175/JHM-D-13-0197.1.

Mo, Kingtse C., Jae-Kyung E. Schemm, and Soo-Hyun Yoo. 2009. "Influence of ENSO and the Atlantic Multidecadal Oscillation on Drought over the United States." Journal of Climate 22 (22): 5962–82. https://doi.org/10.1175/2009JCLI2966.1.

Monteith, J. L. 1965. "Evaporation and Environment." Symposia of the Society for Experimental Biology 19: 205–34.

Moradkhani, Hamid, and Matthew Meier. 2010. "Long-Lead Water Supply Forecast Using Large-Scale Climate Predictors and Independent Component Analysis." Journal of Hydrologic Engineering 15 (10): 744–62. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000246.

Moreo, Michael T., and Amy Swancar. 2013. "Evaporation from Lake Mead, Nevada and Arizona, March 2010 through February 2012." Scientific Investigations Report 2013–5229. Scientific Investigations Report. U.S. Geological Survey. https://pubs.usgs.gov/sir/2013/5229/.

Mote, Philip W., Levi Brekke, Philip B. Duffy, and Ed Maurer. 2011. "Guidelines for Constructing Climate Scenarios." Eos, Transactions American Geophysical Union 92 (31): 257–58. https://doi.org/10.1029/2011EO310001.

Mote, Philip W., Alan F. Hamlet, Martyn P. Clark, and Dennis P. Lettenmaier. 2005. "Declining Mountain Snowpack in Western North America." Bulletin of the American Meteorological Society 86 (1): 39–50. https://doi.org/10.1175/BAMS-86-1-39.

Mote, Philip W., Sihan Li, Dennis P. Lettenmaier, Mu Xiao, and Ruth Engel. 2018. "Dramatic Declines in Snowpack in the Western US." Npj Climate and Atmospheric Science 1 (1). https://doi.org/10.1038/s41612-018-0012-1.

Mundhenk, Bryan D., Elizabeth A. Barnes, Eric D. Maloney, and Cory F. Baggett. 2018. "Skillful Empirical Subseasonal Prediction of Landfalling Atmospheric River Activity Using the Madden–Julian Oscillation and Quasi-Biennial Oscillation." Npj Climate and Atmospheric Science 1 (1): 20177. https://doi.org/10.1038/s41612-017-0008-2.

Munson, Seth M., Jayne Belnap, and Gregory S. Okin. 2011. "Responses of Wind Erosion to Climate-Induced Vegetation Changes on the Colorado Plateau." Proceedings of the National Academy of Sciences 108 (10): 3854–59. https://doi.org/10.1073/pnas.1014947108.

Naghettini, Mauro. 2016. Fundamentals of Statistical Hydrology. New York, NY: Springer Science+Business Media. https://doi-org.colorado.idm.oclc.org/10.1007/978-3-319-43561-9.

Najafi, Mohammad Reza, and Hamid Moradkhani. 2015. "Ensemble Combination of Seasonal Streamflow Forecasts." Journal of Hydrologic Engineering 21 (1): 04015043. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001250.

NASA. 2019. "Rising to New Challenges for California's Snow Forecasting Program."

Nash, Linda L., and Peter H. Gleick. 1991. "Sensitivity of Streamflow in the Colorado Basin to Climatic Changes." Journal of Hydrology 125 (3–4): 221–41. https://doi.org/10.1016/0022-1694(91)90030-L.

Nathanson, Milton. 1978. "Updating the Hoover Dam Documents, 1978." Reclamation. http://www.riversimulator.org/Resources/LawOfTheRiver/HooverDamDocs/UpdatingHoover1978.pdf.

National Academies, Board on Atmospheric Sciences and Climate, Ocean Studies Board, Division on Earth and Life Studies, and National Academies of Sciences, Engineering, and Medicine. 2016. Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts. Washington, D.C.: National Academies Press. https://doi.org/10.17226/21873.

National Interagency Fire Center. n.d. "Remote Automatic Weather Stations (RAWS)." Remote Automatic Weather Stations. https://raws.nifc.gov/.

National Oceanic and Atmospheric Administration. 2019. "Cooperative Observer Network." Cooperative Observer Network. 2019. https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/cooperative-observer-network-coop.

———. n.d. "Automated Surface Observing System (ASOS)." Automated Surface Observing System. https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/automated-surface-observing-system-asos.

———. n.d. "Automated Weather Observing System (AWOS)." Automated Weather Observing System. https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/automated-weather-observing-system-awos.

———. n.d. "CLIMGRID." Readme File for CLIMGRID. https://data.noaa.gov/dataset/dataset/gridded-5km-ghcn-daily-temperature-and-precipitation-dataset-version-1/resource/72ce7666-9b67-4f58-b433-d9db15320702.

National Research Council. 2003. Critical Issues in Weather Modification Research. Washington, D.C.: National Academies Press. https://doi.org/10.17226/10829.

———. 2004. Assessing the National Streamflow Information Program. https://doi.org/10.17226/10967.

———. 2007. Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability. Washington, D.C.: National Academies Press. https://doi.org/10.17226/11857.

National Weather Service. n.d. "Automated Surface Observing Systems." ASOS National Program Automated Surface Observing Systems. https://www.weather.gov/asos/asostech.

———. n.d. "Cooperative Observer Program (COOP)." Cooperative Observer Program. https://www.weather.gov/coop/overview.

National Wildfire Coordinating Group. 2014. “Interagency Wildland Fire Weather Station Standards & Guidelines,” 50.

Natural Resource Conservation Service. n.d. “Automated Soil Climate Monitoring.” Automated Soil Climate Monitoring. https://www.wcc.nrcs.usda.gov/about/mon_scan.html.

———. n.d. “Snow Telemetry (SNOTEL) and Snow Course Data and Products.” Snow Telemetry and Snow Course Data and Products. https://www.wcc.nrcs.usda.gov/snow/.

NCAR, Weather Modification Incorporated, University of Wyoming, Heritage Environmental Consultants, Desert Research Institute (DRI), and University of Alabama. 2014. “The Wyoming Weather Modification Project Pilot Program: Level II Study. Draft Executive Summary.” Wyoming Water Development Commission. http://wwdc.state.wy.us/weathermod/WYWeatherModPilotProgramExecSummary.html.

Nearing, Grey S., Benjamin L. Ruddell, Martyn P. Clark, Bart Nijssen, and Christa Peters-Lidard. 2018. “Benchmarking and Process Diagnostics of Land Models.” Journal of Hydrometeorology 19 (11): 1835–52. https://doi.org/10.1175/JHM-D-17-0209.1.

Neff, J. C., A. P. Ballantyne, G. L. Farmer, N. M. Mahowald, J. L. Conroy, C. C. Landry, J. T. Overpeck, T. H. Painter, C. R. Lawrence, and R. L. Reynolds. 2008. “Increasing Eolian Dust Deposition in the Western United States Linked to Human Activity.” Nature Geoscience 1 (3): 189–95. https://doi.org/10.1038/ngeo133.

Newman, Andrew J., Martyn P. Clark, Jason Craig, Bart Nijssen, Andrew W. Wood, Ethan D. Gutmann, Naoki Mizukami, Levi Brekke, and Jeff R. Arnold. 2015. “Gridded Ensemble Precipitation and Temperature Estimates for the Contiguous United States.” Journal of Hydrometeorology 16 (6): 2481–2500. https://doi.org/10.1175/JHM-D-15-0026.1.

Newman, Andrew J., Martyn P. Clark, Ryan J. Longman, and Thomas W. Giambelluca. 2019. “Methodological Intercomparisons of Station-Based Gridded Meteorological Products: Utility, Limitations, and Paths Forward.” Journal of Hydrometeorology 20 (3): 531–47. https://doi.org/10.1175/JHM-D-18-0114.1.

Newman, Matthew, Michael A. Alexander, Toby R. Ault, Kim M. Cobb, Clara Deser, Emanuele Di Lorenzo, Nathan J. Mantua, et al. 2016. “The Pacific Decadal Oscillation, Revisited.” Journal of Climate 29 (12): 4399–4427. https://doi.org/10.1175/JCLI-D-15-0508.1.

Newman, Matthew, Gilbert P. Compo, and Michael A. Alexander. 2003. “ENSO-Forced Variability of the Pacific Decadal Oscillation.” Journal of Climate 16 (23): 3853–57. https://doi.org/10.1175/1520-0442(2003)016<3853:EVOTPD>2.0.CO;2.

Niu, Guo-Yue, Zong-Liang Yang, Kenneth E. Mitchell, Fei Chen, Michael B. Ek, Michael Barlage, Anil Kumar, et al. 2011. “The Community Noah Land Surface Model with Multiparameterization Options (Noah-MP): 1. Model Description and Evaluation with Local-Scale Measurements.” Journal of Geophysical Research: Atmospheres 116 (D12). https://doi.org/10.1029/2010JD015139.

NOAA Earth System Research Laboratory. n.d. “Livneh Daily CONUS Near-Surface Gridded Meteorological and Derived Hydrometeorological Data.” Livneh Daily CONUS Near-Surface Gridded Meteorological and Derived Hydrometeorological Data. https://www.esrl.noaa.gov/psd/data/gridded/data.livneh.html.

NOAA National Centers for Environmental Information. n.d. “U.S. Climate Reference Network.” Accessed November 17, 2019. https://www.ncdc.noaa.gov/crn/.

NOAA National Environmental, Satellite, Data, and Information Service. 2007. “United States Climate Reference Network Functional Requirements Document.” US Department of Commerce. NOAA-CRN/OSD-2003-0009R1UD0.

Nowak, Kenneth, Martin P. Hoerling, Balaji Rajagopalan, and Edith Zagona. 2012. “Colorado River Basin Hydroclimatic Variability.” Journal of Climate 25 (12): 4389–4403. https://doi.org/10.1175/JCLI-D-11-00406.1.

Nowak, Kenneth, James Prairie, Balaji Rajagopalan, and Upmanu Lall. 2010. "A Nonparametric Stochastic Approach for Multisite Disaggregation of Annual to Daily Streamflow." Water Resources Research 46 (8). https://doi.org/10.1029/2009WR008530.

NRCS. n.d. "NRCS (Natural Resources Conservation Service) Interactive Map 4.0." Accessed June 21, 2019. https://www.wcc.nrcs.usda.gov/webmap_beta/index.html.

Oaida, Catalina M., John T. Reager, Konstantinos M. Andreadis, Cédric H. David, Steve R. Levoe, Thomas H. Painter, Kat J. Bormann, Amy R. Trangsrud, Manuela Girotto, and James S. Famiglietti. 2019. "A High-Resolution Data Assimilation Framework for Snow Water Equivalent Estimation across the Western United States and Validation with the Airborne Snow Observatory." Journal of Hydrometeorology 20 (3): 357–78. https://doi.org/10.1175/JHM-D-18-0009.1.

Okumura, Yuko M., Pedro DiNezio, and Clara Deser. 2017. "Evolving Impacts of Multiyear La Niña Events on Atmospheric Circulation and U.S. Drought." Geophysical Research Letters 44 (22): 11,614-11,623. https://doi.org/10.1002/2017GL075034.

O'Lenic, Edward A., David A. Unger, Michael S. Halpert, and Kenneth S. Pelman. 2008. "Developments in Operational Long-Range Climate Prediction at CPC." Weather and Forecasting 23 (3): 496–515. https://doi.org/10.1175/2007WAF2007042.1.

O'Neill, Brian C., Claudia Tebaldi, Detlef P. van Vuuren, Veronika Eyring, Pierre Friedlingstein, George Hurtt, Reto Knutti, et al. 2016. "The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6." Geoscientific Model Development 9 (9): 3461–82. https://doi.org/10.5194/gmd-9-3461-2016.

Ostler, Don A. 2017. "Sixty-Ninth Annual Report of the Upper Colorado River Commission." Annual report 69. Salt Lake City, UT: Upper Colorado River Commission. http://www.ucrcommission.com/RepDoc/UCRCAnnualReports/69_UCRC_Annual_Report.pdf.

Ouarda, Taha B. M. J., John W. Labadie, and Darrell G. Fontane. 1997. "Indexed Sequential Hydrologic Modeling for Hyropower Capacity Estimation." Journal of the American Water Resources Association 33 (6): 1337–49. https://doi.org/10.1111/j.1752-1688.1997.tb03557.x.

Oyler, Jared W. n.d. "TopoWx." ScriMHub. http://www.scrimhub.org/resources/topowx/.

Oyler, Jared W., Ashley Ballantyne, Kelsey Jencso, Michael Sweet, and Steven W. Running. 2015. "Creating a Topoclimatic Daily Air Temperature Dataset for the Conterminous United States Using Homogenized Station Data and Remotely Sensed Land Skin Temperature." International Journal of Climatology 35 (9): 2258–79. https://doi.org/10.1002/joc.4127.

Oyler, Jared W., Solomon Z. Dobrowski, Ashley P. Ballantyne, Anna E. Klene, and Steven W. Running. 2015. "Artificial Amplification of Warming Trends across the Mountains of the Western United States." Geophysical Research Letters 42 (1): 153–61. https://doi.org/10.1002/2014GL062803.

Oyler, Jared W., Solomon Z. Dobrowski, Zachary A. Holden, and Steven W. Running. 2016. "Remotely Sensed Land Skin Temperature as a Spatial Predictor of Air Temperature across the Conterminous United States." Journal of Applied Meteorology and Climatology 55 (7): 1441–57. https://doi.org/10.1175/JAMC-D-15-0276.1.

Ozdogan, Mutlu, Yang Yang, George Allez, and Chelsea Cervantes. 2010. "Remote Sensing of Irrigated Agriculture: Opportunities and Challenges." Remote Sensing 2 (9): 2274–2304. https://doi.org/10.3390/rs2092274.

Pagano, Thomas C., and David C. Garen. 2005. "A Recent Increase in Western U.S. Streamflow Variability and Persistence." Journal of Hydrometeorology 6 (2): 173–79. https://doi.org/10.1175/JHM410.1.

Pagano, Thomas C., David C. Garen, Tom R. Perkins, and Phillip A. Pasteris. 2009. "Daily Updating of Operational Statistical Seasonal Water Supply Forecasts for the Western U.S.1." JAWRA Journal of the American Water Resources Association 45 (3): 767–78. https://doi.org/10.1111/j.1752-1688.2009.00321.x.

Pagano, Thomas C., David Garen, and Soroosh Sorooshian. 2004. "Evaluation of Official Western U.S. Seasonal Water Supply Outlooks, 1922–2002." Journal of Hydrometeorology 5: 14.

Pagano, Thomas C., Andrew W. Wood, Kevin Werner, and Rashawn Tama-Sweet. 2014. "Western U.S. Water Supply Forecasting: A Tradition Evolves." Eos, Transactions American Geophysical Union 95 (3): 28–29. https://doi.org/10.1002/2014EO030007.

Painter, Thomas H., Andrew P. Barrett, Christopher C. Landry, Jason C. Neff, Maureen P. Cassidy, Corey R. Lawrence, Kathleen E. McBride, and G. Lang Farmer. 2007. "Impact of Disturbed Desert Soils on Duration of Mountain Snow Cover." Geophysical Research Letters 34 (12). https://doi.org/10.1029/2007GL030284.

Painter, Thomas H., Daniel F. Berisford, Joseph W. Boardman, Kathryn J. Bormann, Jeffrey S. Deems, Frank Gehrke, Andrew Hedrick, et al. 2016. "The Airborne Snow Observatory: Fusion of Scanning Lidar, Imaging Spectrometer, and Physically-Based Modeling for Mapping Snow Water Equivalent and Snow Albedo." Remote Sensing of Environment 184 (October): 139–52. https://doi.org/10.1016/j.rse.2016.06.018.

Painter, Thomas H., Ann C. Bryant, and S. McKenzie Skiles. 2012. "Radiative Forcing of Dust in Mountain Snow from MODIS Surface Reflectance Data." Geophysical Research Letters 39 (L17502).

Painter, Thomas H., Jeffrey S. Deems, Jayne Belnap, Alan F. Hamlet, Christopher C. Landry, and Bradley Udall. 2010. "Response of Colorado River Runoff to Dust Radiative Forcing in Snow." Proceedings of the National Academy of Sciences 107 (40): 17125–30. https://doi.org/10.1073/pnas.0913139107.

Painter, Thomas H., Karl Rittger, Ceretha McKenzie, Peter Slaughter, Robert E. Davis, and Jeff Dozier. 2009. "Retrieval of Subpixel Snow Covered Area, Grain Size, and Albedo from MODIS." Remote Sensing of Environment 113 (4): 868–79. https://doi.org/10.1016/j.rse.2009.01.001.

Painter, Thomas H., S. McKenzie Skiles, Jeffrey S. Deems, W. Tyler Brandt, and Jeff Dozier. 2018. "Variation in Rising Limb of Colorado River Snowmelt Runoff Hydrograph Controlled by Dust Radiative Forcing in Snow." Geophysical Research Letters 45 (2): 797–808. https://doi.org/10.1002/2017GL075826.

Painter, Thomas H., S. McKenzie Skiles, Jeffrey S. Deems, Ann C. Bryant, and Christopher C. Landry. 2012. "Dust Radiative Forcing in Snow of the Upper Colorado River Basin: 1. A 6 Year Record of Energy Balance, Radiation, and Dust Concentrations." Water Resources Research 48 (7). https://doi.org/10.1029/2012WR011985.

Panofsky, Hans A., and G. Brier. 1968. Some Applications of Statistics to Meteorology. Earth and Mineral Sciences Continuing Education, College of Earth and Mineral Sciences.

Pederson, Gregory T., Julio L. Betancourt, and Gregory J. McCabe. 2013. "Regional Patterns and Proximal Causes of the Recent Snowpack Decline in the Rocky Mountains, U.S." Geophysical Research Letters 40 (9): 1811–16. https://doi.org/10.1002/grl.50424.

Pederson, Gregory T., Stephen T. Gray, Connie A. Woodhouse, Julio L. Betancourt, Daniel B. Fagre, Jeremy S. Littell, Emma Watson, Brian H. Luckman, and Lisa J. Graumlich. 2011. "The Unusual Nature of Recent Snowpack Declines in the North American Cordillera." Science 333 (6040): 332–35. https://doi.org/10.1126/science.1201570.

Pegion, Kathy, Ben P. Kirtman, Emily Becker, Dan C. Collins, Emerson LaJoie, Robert Burgman, Ray Bell, et al. 2019. "The Subseasonal Experiment (SubX): A Multi-Model Subseasonal Prediction Experiment." Bulletin of the American Meteorological Society, July, BAMS-D-18-0270.1. https://doi.org/10.1175/BAMS-D-18-0270.1.

Pendergrass, Angeline G., Reto Knutti, Flavio Lehner, Clara Deser, and Benjamin M. Sanderson. 2017. "Precipitation Variability Increases in a Warmer Climate." Scientific Reports 7 (1). https://doi.org/10.1038/s41598-017-17966-y.

Penman, H. L. 1948. "Natural Evaporation from Open Water, Bare Soil and Grass." Proceedings of the Royal Society A 193 (1032). https://doi.org/10.1098/rspa.1948.0037.

Peterson, Thomas C., David R. Easterling, Thomas R. Karl, Pavel Groisman, Neville Nicholls, Neil Plummer, Simon Torok, et al. 1998. "Homogeneity Adjustments of in Situ Atmospheric Climate Data: A Review." International Journal of Climatology 18 (13): 1493–1517. https://doi.org/10.1002/(SICI)1097-0088(19981115)18:13<1493::AID-JOC329>3.0.CO;2-T.

Peterson, Thomas C., Russell Vose, Richard Schmoyer, and Vyachevslav Razuvaëv. 1998. "Global Historical Climatology Network (GHCN) Quality Control of Monthly Temperature Data." International Journal of Climatology 18 (11): 1169–79. https://doi.org/10.1002/(SICI)1097-0088(199809)18:11<1169::AID-JOC309>3.0.CO;2-U.

Phillips, Morgan. 2013. "Estimates of Sublimation in the Upper Colorado River Basin." Master's, Colorado State University.

Piechota, Thomas C., Francis H. S. Chiew, John A. Dracup, and Thomas A. McMahon. 1998. "Seasonal Streamflow Forecasting in Eastern Australia and the El Niño–Southern Oscillation." Water Resources Research 34 (11): 3035–44. https://doi.org/10.1029/98WR02406.

Pierce, David W., Tim P. Barnett, Hugo G. Hidalgo, Tapash Das, Céline Bonfils, Benjamin D. Santer, Govindasamy Bala, et al. 2008. "Attribution of Declining Western U.S. Snowpack to Human Effects." Journal of Climate 21 (23): 6425–44. https://doi.org/10.1175/2008JCLI2405.1.

Pierce, David W., Tim P. Barnett, B. D. Santer, and P. J. Gleckler. 2009. "Selecting Global Climate Models for Regional Climate Change Studies." Proceedings of the National Academy of Sciences 106 (21): 8441–46. https://doi.org/10.1073/pnas.0900094106.

Pierce, David W., Daniel R. Cayan, Edwin P. Maurer, John T. Abatzoglou, and Katherine C. Hegewisch. 2015. "Improved Bias Correction Techniques for Hydrological Simulations of Climate Change." Journal of Hydrometeorology 16 (6): 2421–42. https://doi.org/10.1175/JHM-D-14-0236.1.

Pierce, David W., Daniel R. Cayan, and Bridget L. Thrasher. 2014. "Statistical Downscaling Using Localized Constructed Analogs (LOCA)." Journal of Hydrometeorology 15 (6): 2558–85. https://doi.org/10.1175/JHM-D-14-0082.1.

Pierce, David W., Julie F. Kalansky, and Daniel R. Cayan. 2018. "Climate, Drought, and Sea Level Scenarios for California's Fourth Climate Change Assessment."

"Plans & Reports | Upper Colorado Region | Bureau of Reclamation." n.d. Accessed December 12, 2019. https://www.usbr.gov/uc/envdocs/plans.html#CCULR.

Powell, Anthony. 2015. "Utilizing Probabilistic Forecasts for Colorado River Reservoir Operations Using a Mid-Term Probabilistic Operations Model for Decision Making and Risk Management." In Reno, NV, 11. Reno, NV: Advisory Committee on Water Information.

Powell Consortium. 1995. "Severe Sustained Drought, Managing the Colorado River System in Time of Water Shortage."

Prairie, James, and Russell Callejo. 2005. "Natural Flow and Salt Computation Methods, Calendar Years 1971-1995." US Bureau of Reclamation.

Prairie, James, Kenneth Nowak, Balaji Rajagopalan, Upmanu Lall, and Terrance Fulp. 2008. "A Stochastic Nonparametric Approach for Streamflow Generation Combining Observational and Paleoreconstructed Data: An Approach for Streamflow Generation." Water Resources Research 44 (6). https://doi.org/10.1029/2007WR006684.

Prairie, James, Balaji Rajagopalan, Terry J. Fulp, and Edith A. Zagona. 2006. "Modified K-NN Model for Stochastic Streamflow Simulation." Journal of Hydrologic Engineering 11 (4): 371–78. https://doi.org/10.1061/(ASCE)1084-0699(2006)11:4(371).

Prairie, James, Balaji Rajagopalan, Upmanu Lall, and Terrance Fulp. 2007. "A Stochastic Nonparametric Technique for Space-Time Disaggregation of Streamflows." Water Resources Research 43 (3). https://doi.org/10.1029/2005WR004721.

Prein, Andreas F., Wolfgang Langhans, Giorgia Fosser, Andrew Ferrone, Nikolina Ban, Klaus Goergen, Michael Keller, et al. 2015. "A Review on Regional Convection-permitting Climate Modeling: Demonstrations, Prospects, and Challenges." Reviews of Geophysics 53 (2): 323–61. https://doi.org/10.1002/2014RG000475.

PRISM. 2016. "Descriptions of PRISM Spatial Climate Datasets for the Conterminous United States." http://www.prism.oregonstate.edu/documents/PRISM_datasets.pdf.

Quayle, Robert Q., David R. Easterling, Thomas R. Karl, and Pamela J. Hughes. 1991. "Effects of Recent Thermomenter Changes in the Cooperative Station Network." Bulletin of the American Meteorological Society 72 (11): 1718–23.

Raff, David, Levi Brekke, Kevin Werner, Andy Wood, and Kathleen White. 2013. "Short-Term Water Management Decisions: User Needs for Improved Climate, Weather, and Hydrologic Information." Technical report CWTS 2013-1. U.S. Army Corps of Engineers. https://www.usbr.gov/research/st/roadmaps/WaterSupply.pdf.

Rajagopalan, Balaji, Kenneth Nowak, James Prairie, Martin Hoerling, Benjamin Harding, Joseph Barsugli, Andrea Ray, and Bradley Udall. 2009. "Water Supply Risk on the Colorado River: Can Management Mitigate?" Water Resources Research 45 (8). https://doi.org/10.1029/2008WR007652.

Ralph, F. Martin, Jonathan J. Rutz, Jason M. Cordeira, Michael Dettinger, Michael Anderson, David Reynolds, Lawrence J. Schick, and Chris Smallcomb. 2019. "A Scale to Characterize the Strength and Impacts of Atmospheric Rivers." Bulletin of the American Meteorological Society 100 (2): 269–89. https://doi.org/10.1175/BAMS-D-18-0023.1.

Rangwala, Imtiaz, Tim Bardsley, Marcus Pescinski, and Jim Miller. 2015. "SNOTEL Sensor Upgrade Has Caused Temperature Record Inhomogeneities for the Intermountain West: Implications for Climate Change Impact Assessments." Research Briefing. University of Colorado Boulder: Western Water Assessement.

Rangwala, Imtiaz, and James R. Miller. 2010. "Twentieth Century Temperature Trends in Colorado's San Juan Mountains." Arctic, Antarctic, and Alpine Research 42 (1): 89–97. https://doi.org/10.1657/1938-4246-42.1.89.

Rangwala, Imtiaz, Lesley L. Smith, Gabriel Senay, Joseph J. Barsugli, Stefanie Kagone, and Michael T. Hobbins. 2019. "Landscape Evaporative Response Index (LERI): A High Resolution Monitoring and Assessment of Evapotranspiration across the Contiguous United States." National and Regional Climate Adaptation Science Centers. https://doi.org/10.21429/43r4-3q68.

"Rapid Refresh (RAP)." n.d. Accessed December 11, 2019. https://rapidrefresh.noaa.gov/.

Rasmussen, Roy, Bruce Baker, John Kochendorfer, Tilden Meyers, Scott Landolt, Alexandre P. Fischer, Jenny Black, et al. 2012. "How Well Are We Measuring Snow: The NOAA/FAA/NCAR Winter Precipitation Test Bed." Bulletin of the American Meteorological Society 93 (6): 811–29. https://doi.org/10.1175/BAMS-D-11-00052.1.

Rasmussen, Roy, Kyoko Ikeda, Changhai Liu, David Gochis, Martyn P. Clark, Aiguo Dai, Ethan D. Gutmann, et al. 2014. "Climate Change Impacts on the Water Balance of the Colorado Headwaters: High-Resolution Regional Climate Model Simulations." Journal of Hydrometeorology 15 (3): 1091–1116. https://doi.org/10.1175/JHM-D-13-0118.1.

Rasmussen, Roy, Changhai Liu, Kyoko Ikeda, David Gochis, David Yates, Fei Chen, Mukul Tewari, et al. 2011. "High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate." Journal of Climate 24 (12): 3015–48. https://doi.org/10.1175/2010JCLI3985.1.

Rasmussen, Roy, Sarah Tessendorf, Lulin Xue, Courtney Weeks, Kyoko Ikeda, Scott Landolt, Dan Breed, Terry Deshler, and Barry Lawrence. 2018. "Evaluation of the Wyoming Weather Modification Pilot Project (WWMPP) Using Two Approaches: Traditional Statistics and Ensemble Modeling." Journal of Applied Meteorology and Climatology 57 (11): 2639–60. https://doi.org/10.1175/JAMC-D-17-0335.1.

Rasmusson, Eugene M., and Thomas H. Carpenter. 1982. "Variations in Tropical Sea Surface Temperature and Surface Wind Fields Associated with the Southern Oscillation/El Niño." Monthly Weather Review 110: 354–84. https://doi.org/10.1175/1520-0493(1982)110<0354:VITSST>2.0.CO;2.

Rauber, Robert M., Bart Geerts, Lulin Xue, Jeffrey French, Katja Friedrich, Roy M. Rasmussen, Sarah A. Tessendorf, Derek R. Blestrud, Melvin L. Kunkel, and Shaun Parkinson. 2019. "Wintertime Orographic Cloud Seeding—A Review." Journal of Applied Meteorology and Climatology 58 (10): 2117–40. https://doi.org/10.1175/JAMC-D-18-0341.1.

Ray, Andrea J., Joseph J. Barsugli, K. B. Averyt, Klaus Wolter, Martin P. Hoerling, Nolan J. Doesken, Bradley Udall, and R. S. Webb. 2008. "Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation." https://wwa.colorado.edu/publications/reports/WWA_ClimateChangeColoradoReport_2008.pdf.

Reclamation. 1969. "Report of the Committee on Probabilities and Test Studies to the Task Force on Operating Criteria for the Colorado River." US Bureau of Reclamation. http://www.riversimulator.org/Resources/USBR/ProbabilitiesOnOperatingCriteriaColoradoRiverBoR1969opt.pdf.

———. 1983. "Colorado River Simulation System Hydrology Data Base." US Bureau of Reclamation. https://www.usbr.gov/lc/region/g4000/NaturalFlow/Upper%20Basin_CRSS%20Hydrology%20Data_Base_1983.pdf.

———. 1985. Colorado River Simulation System CRSS System Overview. Denver, Colorado.

———. 1986. "Lake Powell Evaporation." Salt Lake City, UT: Upper Colorado Regional Office.

———. 2007a. "Draft EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead, Appendix A – CRSS Model Documentation." https://www.usbr.gov/lc/region/programs/strategies/draftEIS/AppA.pdf.

———. 2007b. "Final EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, Appendix N – Analysis of Hydrologic Variability Sensitivity." https://www.usbr.gov/lc/region/programs/strategies/FEIS/index.html.

———. 2007c. "Final EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, Appendix U – Review of Science and Methods for Incorporating Climate Change Information into Reclamation's Colorado River Basin Planning Studies." https://www.usbr.gov/lc/region/programs/strategies/FEIS/index.html#VolIII.

———. 2007d. "Final EIS, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead, Appendix C-Upper Basin States Depletion Schedules." US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/strategies/FEIS/AppC.pdf.

———. 2007e. "Final EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, Chapter 1-Purpose and Need." https://www.usbr.gov/lc/region/programs/strategies/FEIS/Chp1.pdf.

———. 2007f. "Final EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, Volume 1." https://www.usbr.gov/lc/region/programs/strategies/FEIS/Vol1Front.pdf.

———. 2010. "Colorado River Modeling Work Group Charter." https://www.usbr.gov/lc/region/programs/climateresearch/Charter_ModelingWorkGroup.pdf.

———. 2011. "West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections." Technical Memorandum No. 86-68210-2011-01.

———. 2012a. “Colorado River Basin Water Supply and Demand Study, Appendix C11.” https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20C%20-%20Water%20Demand%20Assessment/TR-C_Appendix11_FINAL.pdf.
———. 2012b. “Colorado River Basin Water Supply and Demand Study, Technical Report B-Water Supply Assessment.” US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20B%20-%20Water%20Supply%20Assessment/TR-B_Water_Supply_Assessment_FINAL.pdf.
———. 2012c. “Colorado River Basin Water Supply and Demand Study-Appendix B4, Variable Infiltration Capacity (VIC) Hydrologic Modeling Methods and Simulations.” US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20B%20-%20Water%20Supply%20Assessment/TR-B_Appendix4_FINAL.pdf.
———. 2012d. “Colorado River Basin Water Supply and Demand Study-Technical Report C.” Technical report. US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20C%20-%20Water%20Demand%20Assessment/TR-C-Water_Demand_Assessmemt_FINAL.pdf.
———. 2012e. “Colorado River Basin Water Supply and Demand Study.” US Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Study%20Report/CRBS_Study_Report_FINAL.pdf.
———. 2012f. “Colorado River Basin Water Supply and Demand Study-Technical Report G, CRSS Modeling Assumptions.” https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20G%20-%20System%20Reliability%20Analysis%20and%20Evaluation%20of%20Options%20and%20Stat egies/TR-G_Appendix2_FINAL_Dec2012.pdf.
———. 2014. “Downscaled CMIP3 and CMIP5 Hydrology Projections – Release of Hydrology Projections, Comparison with Preceding Information and Summary of User Needs.” Department of Interior, US Bureau of Reclamation.
———. 2015a. “Colorado River Basin Mid-Term Probabilistic Operations Model (MTOM) Overview and Description.” US Bureau of Reclamation.
———. 2015b. “Law of the Riverl Lower Colorado Region l Bureau of Reclamation.” USBR.Gov. June 30, 2015. https://www.usbr.gov/lc/region/pao/lawofrvr.html.
———. 2016a. “Downscaled CMIP3 and CMIP5 Climate Projections - Addendum: Release of Downscaled CMIP5 Climate Projections (LOCA) and Comparison with Preceding Information.” Reclamation. http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/.
———. 2016b. “SECURE Water Act Section 9503(c)— Reclamation Climate Change and Water 2016.” US Bureau of Reclamation.
———. 2016c. “Colorado River Accounting and Water Use Report: Arizona, California, and Nevada Calendar Year 2015.” US Bureau of Reclamation. https://www.usbr.gov/lc/region/g4000/4200Rpts/DecreeRpt/2015/2015.pdf.
———. 2018. “Colorado River Basin Ten Tribes Partnership Tribal Water Study.” https://www.usbr.gov/lc/region/programs/crbstudy/tws/finalreport.html.
———. 2019a. “AgriMet.” Agrimet. 2019. https://www.usbr.gov/pn/agrimet/proginfo.html.
———. 2019b. “Draft -Binational Task 4, Evaluation of Reclamation’s 24-Month Study.”
———. 2019c. “Colorado River Basin Drought Contingency Plans-Final Documents.” November 2019. https://www.usbr.gov/dcp/finaldocs.html.
———. 2019d. “Colorado River Basin Natural Flow and Salt Data.” April 1, 2019. https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html.
———. 2020. “Exploring Climate and Hydrology Projections from the CMIP5 Archive.” US Bureau of Reclamation.

Reclamation, and Colorado Basin River Forecast Center. in preparation. “Draft - Forecast and Reservoir Operation Modeling Uncertainty Scoping (FROMUS) Report.”

Redmond, Kelly T. 2003. “Climate Variability in the West: Complex Spatial Structure Associated with Topography, and Observational Issues.” In Water and Climate in the Western United States, 29–48. University of Colorado Press.

Redmond, Kelly T., and Roy W. Koch. 1991. “Surface Climate and Streamflow Variability in the Western United States and Their Relationship to Large-Scale Circulation Indices.” Water Resources Research 27 (9): 2381–99. https://doi.org/10.1029/91WR00690.

Reges, Henry W., Nolan Doesken, Julian Turner, Noah Newman, Antony Bergantino, and Zach Schwalbe. 2016. “CoCoRaHS: The Evolution and Accomplishments of a Volunteer Rain Gauge Network.” Bulletin of the American Meteorological Society 97 (10): 1831–46. https://doi.org/10.1175/BAMS-D-14-00213.1.

Reggiani, Paolo, Murugesu Sivapalan, and S. Majid Hassanizadeh. 1998. “A Unifying Framework for Watershed Thermodynamics: Balance Equations for Mass, Momentum, Energy and Entropy, and the Second Law of Thermodynamics.” Advances in Water Resources 22 (4): 367–98. https://doi.org/10.1016/S0309-1708(98)00012-8.

Regonda, Satish Kumar, Balaji Rajagopalan, Martyn P. Clark, and John Pitlick. 2005. “Seasonal Cycle Shifts in Hydroclimatology over the Western United States.” Journal of Climate 18 (2): 372–84. https://doi.org/10.1175/JCLI-3272.1.

Revelle, R. R., and P. E. Waggoner. 1983. “Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States.” Report of the Carbon Dioxide Assessment Committee. Washington, D.C.: National Academy of Sciences, National Academy Press.

Reynolds, David. 2015. “Literature Review and Scientific Synthesis on the Efficacy of Winter Orographic Cloud Seeding - A Report to the Bureau of Reclamation.” CIRES. https://wcr.colorado.edu/sites/default/files/project/files/Literature%20Review%20and%20Scientific%20Synthesis%20on%20the%20Efficacy%20of%20Winter%20Orographic%20Cloud%20Seeding_BOR_June%2010%202015_with%20Exec%20Summary_0.pdf.

Rice, Jennifer L., Connie A. Woodhouse, and Jeffrey J. Lukas. 2009. “Science and Decision Making: Water Management and Tree-Ring Data in the Western United States.” JAWRA Journal of the American Water Resources Association 45 (5): 1248–59. https://doi.org/10.1111/j.1752-1688.2009.00358.x.

Ritchie, Justin, and Hadi Dowlatabadi. 2017. “Why Do Climate Change Scenarios Return to Coal?” Energy 140 (December): 1276–91. https://doi.org/10.1016/j.energy.2017.08.083.

Robertson, Andrew W., and Frédéric Vitart. 2019. Sub-Seasonal to Seasonal Prediction. Elsevier.

Robertson, D. E., P. Pokhrel, and Q. J. Wang. 2013. “Improving Statistical Forecasts of Seasonal Streamflows Using Hydrological Model Output.” Hydrology and Earth System Sciences 17 (2): 579–93. https://doi.org/10.5194/hess-17-579-2013.

Ropelewski, Chester F., and Michael S. Halpert. 1987. “Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation (ENSO).” Monthly Weather Review 115: 1606–26. https://doi.org/10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2.

———. 1989. “Precipitation Patterns Associated with the High Index Phase of the Southern Oscillation.” Journal of Climate 2: 268–84. https://doi.org/10.1175/1520-0442(1989)002<0268:PPAWTH>2.0.CO;2.

Rosenberg, Eric A., E. A. Clark, A. C. Steinemann, and Dennis P. Lettenmaier. 2013. “On the Contribution of Groundwater Storage to Interannual Streamflow Anomalies in the Colorado River Basin.” Hydrology and Earth System Sciences 17 (4): 1475–91. https://doi.org/10.5194/hess-17-1475-2013.

Rosenberg, Eric A., Andrew W. Wood, and Anne C. Steinemann. 2011. "Statistical Applications of Physically Based Hydrologic Models to Seasonal Streamflow Forecasts." Water Resources Research 47 (3). https://doi.org/10.1029/2010WR010101.

———. 2013. "Informing Hydrometric Network Design for Statistical Seasonal Streamflow Forecasts." Journal of Hydrometeorology 14 (5): 1587–1604. https://doi.org/10.1175/JHM-D-12-0136.1.

Rumsey, Christine A., Matthew P. Miller, David D. Susong, Fred D. Tillman, and David W. Anning. 2015. "Regional Scale Estimates of Baseflow and Factors Influencing Baseflow in the Upper Colorado River Basin." Journal of Hydrology: Regional Studies 4 (September): 91–107. https://doi.org/10.1016/j.ejrh.2015.04.008.

Running, Steven, and Peter Thornton. 1996. "Generating Daily Surfaces of Temperature and Precipitation over Complex Topography." In GIS and Environmental Modeling: Progress and Research Issues., 93–98. https://scholarworks.umt.edu/ntsg_pubs/60.

Rupp, David E., John T. Abatzoglou, Katherine C. Hegewisch, and Philip W. Mote. 2013. "Evaluation of CMIP5 20th Century Climate Simulations for the Pacific Northwest USA." Journal of Geophysical Research: Atmospheres 118 (19): 10,884-10,906. https://doi.org/10.1002/jgrd.50843.

Rupp, David E., John T. Abatzoglou, and Philip W. Mote. 2017. "Projections of 21st Century Climate of the Columbia River Basin." Climate Dynamics 49 (5–6): 1783–99. https://doi.org/10.1007/s00382-016-3418-7.

Saha, Suranjana, Shrinivas Moorthi, Xingren Wu, Jiande Wang, Sudhir Nadiga, Patrick Tripp, David Behringer, et al. 2014. "The NCEP Climate Forecast System Version 2." Journal of Climate 27 (6): 2185–2208. https://doi.org/10.1175/JCLI-D-12-00823.1.

Salas, Jose D., J. W. Delleur, V. Yevjevich, and W. L. Lane. 1980. Applied Modeling of Hydrologic Time Series. Littleton, Colorado: Water Resources Publications.

Salas, Jose D. 1992. "Analysis and Modeling of Hydrologic Time Series." In Handbook of Hydrology, David R. Maidment, Editor in Chief. McGraw-Hill, Inc.

Salas, Jose D., Donald Frevert, Jeffrey Rieker, David King, Steffen Meyer, William Lane, and Edith Zagona. 2001. "New Developments on the SAMS Stochastic Hydrology Package." In Bridging the Gap, 1–6. The Rosen Plaza Hotel, Orlando, Florida, United States: American Society of Civil Engineers. https://doi.org/10.1061/40569(2001)143.

Samaniego, Luis, Rohini Kumar, and Sabine Attinger. 2010. "Multiscale Parameter Regionalization of a Grid-Based Hydrologic Model at the Mesoscale." Water Resources Research 46 (5). https://doi.org/10.1029/2008WR007327.

Sammis, Theodore W., Junming Wang, and David R. Miller. 2011. "The Transition of the Blaney-Criddle Formula to the Penman-Monteith Equation in the Western United States," 12.

Sanderson, Benjamin M., Michael Wehner, and Reto Knutti. 2017. "Skill and Independence Weighting for Multi-Model Assessments." Geoscientific Model Development 10 (6): 2379–95. https://doi.org/10.5194/gmd-10-2379-2017.

Scanlon, Bridget R., Zizhan Zhang, Robert C. Reedy, Donald R. Pool, Himanshu Save, Di Long, Jianli Chen, David M. Wolock, Brian D. Conway, and Daniel Winester. 2015. "Hydrologic Implications of GRACE Satellite Data in the Colorado River Basin." Water Resources Research 51 (12): 9891–9903. https://doi.org/10.1002/2015WR018090.

Scanlon, Bridget R., Zizhan Zhang, Himanshu Save, Alexander Y. Sun, Hannes Müller Schmied, Ludovicus P. H. van Beek, David N. Wiese, et al. 2018. "Global Models Underestimate Large Decadal Declining and Rising Water Storage Trends Relative to GRACE Satellite Data." Proceedings of the National Academy of Sciences 115 (6): E1080–89. https://doi.org/10.1073/pnas.1704665115.

Schaake, John C., Qingyun Duan, Vazken Andréassian, Stewart Franks, Alan Hall, and George Leavesley. 2006. "The Model Parameter Estimation Experiment (MOPEX)." Journal of Hydrology, The model parameter estimation experiment, 320 (1): 1–2. https://doi.org/10.1016/j.jhydrol.2005.07.054.

Schaake, John C., Qingyun Duan, Victor Koren, Kenneth E. Mitchell, Paul R. Houser, Eric F. Wood, Alan Robock, et al. 2004. "An Intercomparison of Soil Moisture Fields in the North American Land Data Assimilation System (NLDAS)." Journal of Geophysical Research 109 (D1): D01S90. https://doi.org/10.1029/2002JD003309.

Schaefer, Garry L., and Ron F. Paetzold. 2001. "SNOTEL (SNOwpack TELemetry) and SCAN (Soil Climate Analysis Network)." In Proc. Intl. Workshop on Automated Weather Stations for Applications in Agriculture and Water Resources Management:, 7. Lincoln, NE.

Schlesinger, Michael E., and Navin Ramankutty. 1994. "Low-Frequency Oscillation." Nature 372 (6506): 508–9. https://doi.org/10.1038/372508a0.

Schneider, Dominik, and Noah P. Molotch. 2016. "Real-Time Estimation of Snow Water Equivalent in the Upper Colorado River Basin Using MODIS-Based SWE Reconstructions and SNOTEL Data." Water Resources Research 52 (10): 7892–7910. https://doi.org/10.1002/2016WR019067.

Schneider, Stephen H. 2002. "Can We Estimate the Likelihood of Climatic Changes at 2100?" Climatic Change 52 (4): 441–51. https://doi.org/10.1023/A:1014276210717.

Schubert, Siegfried, David Gutzler, Hailan Wang, Aiguo Dai, Tom Delworth, Clara Deser, Kirsten Findell, et al. 2009. "A U.S. CLIVAR Project to Assess and Compare the Responses of Global Climate Models to Drought-Related SST Forcing Patterns: Overview and Results." Journal of Climate 22 (19): 5251–72. https://doi.org/10.1175/2009JCLI3060.1.

Schulman, Edmund. 1945. "Tree-Ring Hydrology of the Colorado Basin." University of Arizona Bulletin 15 (4): 51.

———. 1956. Dendroclimatic Changes in Semiarid America. University of Arizona Press, Tucson.

Scott, David W. 2015. Multivariate Density Estimation: Theory, Practice, and Visualization. Somerset, UNITED STATES: John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/ucb/detail.action?docID=1895499.

Seager, Richard, Robert Burgman, Yochanan Kushnir, Amy Clement, Ed Cook, Naomi Naik, and Jennifer Miller. 2008. "Tropical Pacific Forcing of North American Medieval Megadroughts: Testing the Concept with an Atmosphere Model Forced by Coral-Reconstructed SSTs." Journal of Climate 21 (23): 6175–90. https://doi.org/10.1175/2008JCLI2170.1.

Seager, Richard, Naomi Naik, and Gabriel A. Vecchi. 2010. "Thermodynamic and Dynamic Mechanisms for Large-Scale Changes in the Hydrological Cycle in Response to Global Warming." Journal of Climate 23 (17): 4651–68. https://doi.org/10.1175/2010JCLI3655.1.

Seager, Richard, M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, et al. 2007. "Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America." Science 316 (5828): 1181–84. https://doi.org/10.1126/science.1139601.

Seager, Richard, Mingfang Ting, Cuihua Li, Naomi Naik, Ben Cook, Jennifer Nakamura, and Haibo Liu. 2013. "Projections of Declining Surface-Water Availability for the Southwestern United States." Nature Climate Change 3 (5): 482–86. https://doi.org/10.1038/nclimate1787.

SEI. 2019. "WEAP (Water Evaluation and Planning)." 2019. https://www.weap21.org.

Senay, Gabriel B., Michael Budde, James Verdin, and Assefa Melesse. 2007. "A Coupled Remote Sensing and Simplified Surface Energy Balance Approach to Estimate Actual Evapotranspiration from Irrigated Fields." Sensors 7 (6): 979–1000. https://doi.org/10.3390/s7060979.

Seo, Dong-Jun, Lee Cajina, Robert Corby, and Tracy Howieson. 2009. "Automatic State Updating for Operational Streamflow Forecasting via Variational Data Assimilation." Journal of Hydrology 367 (3–4): 255–75. https://doi.org/10.1016/j.jhydrol.2009.01.019.

Seo, Dong-Jun, Victor Koren, and Neftali Cajina. 2003. “Real-Time Variational Assimilation of Hydrologic and Hydrometeorological Data into Operational Hydrologic Forecasting.” Journal of Hydrometeorology 4: 627–41.

Serinaldi, Francesco, and Chris G. Kilsby. 2015. “Stationarity Is Undead: Uncertainty Dominates the Distribution of Extremes.” Advances in Water Resources 77 (March): 17–36. https://doi.org/10.1016/j.advwatres.2014.12.013.

Serreze, Mark C., Martyn P. Clark, Richard L. Armstrong, David A. McGinnis, and Roger S. Pulwarty. 1999. “Characteristics of the Western United States Snowpack from Snowpack Telemetry (SNOTEL) Data.” Water Resources Research 35 (7): 2145–60. https://doi.org/10.1029/1999WR900090.

Seyfried, M. S., and B. P. Wilcox. 1995. “Scale and the Nature of Spatial Variability: Field Examples Having Implications for Hydrologic Modeling.” Water Resources Research 31 (1): 173–84. https://doi.org/10.1029/94WR02025.

Sharifazari, Salman, and Shahab Araghinejad. 2015. “Development of a Nonparametric Model for Multivariate Hydrological Monthly Series Simulation Considering Climate Change Impacts.” Water Resources Management 29 (14): 5309–22. https://doi.org/10.1007/s11269-015-1119-3.

Sharma, Ashish, David G. Tarboton, and Upmanu Lall. 1997. “Streamflow Simulation: A Nonparametric Approach.” Water Resources Research 33 (2): 291–308. https://doi.org/10.1029/96WR02839.

Shelton, M. L. 2009. Hydroclimatology: Perspectives and Applications. Cambridge University Press. https://books.google.com/books?id=7a2TspPRWmsC.

Shen, Chaopeng. 2018. “A Transdisciplinary Review of Deep Learning Research and Its Relevance for Water Resources Scientists.” Water Resources Research 54 (11): 8558–93. https://doi.org/10.1029/2018WR022643.

Shepherd, Theodore G., Emily Boyd, Raphael A. Calel, Sandra C. Chapman, Suraje Dessai, Ioana M. Dima-West, Hayley J. Fowler, et al. 2018. “Storylines: An Alternative Approach to Representing Uncertainty in Physical Aspects of Climate Change.” Climatic Change 151 (3–4): 555–71. https://doi.org/10.1007/s10584-018-2317-9.

Sheppard, Paul R., Andrew C. Comrie, Gregory D. Packin, Kurt Angersbach, and Malcolm K. Hughes. 2002. “The Climate of the US Southwest.” Climate Research 21: 219–38. https://doi.org/10.3354/cr021219.

Siler, Nicholas, Cristian Proistosescu, and Stephen Po-Chedley. 2019. “Natural Variability Has Slowed the Decline in Western U.S. Snowpack since the 1980s.” Geophysical Research Letters 46 (1): 346–55. https://doi.org/10.1029/2018GL081080.

Singh, V. P. 1995. Computer Models of Watershed Hydrology. Highlands Ranch, CO: Water Resources Publications.

Sitterson, Jan, Chris Knightes, Rajbir Parmar, Kurt Wolfe, Muluken Muche, and Brian Avant. 2017. “An Overview of Rainfall-Runoff Model Types.” Washington, D.C.: U.S. Environmental Protection Agency. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=339328&Lab=NERL.

Sivapalan, Murugesu, Günter Blöschl, Lu Zhang, and Rob Vertessy. 2003. “Downward Approach to Hydrological Prediction.” Hydrological Processes 17 (11): 2101–11. https://doi.org/10.1002/hyp.1425.

Skamarock, William C., and Joseph B. Klemp. 2008. “A Time-Split Nonhydrostatic Atmospheric Model for Weather Research and Forecasting Applications.” Journal of Computational Physics 227 (7): 3465–85. https://doi.org/10.1016/j.jcp.2007.01.037.

Skiles, S. McKenzie, Mark Flanner, Joseph M. Cook, Marie Dumont, and Thomas H. Painter. 2018. “Radiative Forcing by Light-Absorbing Particles in Snow.” Nature Climate Change 8 (11): 964–71. https://doi.org/10.1038/s41558-018-0296-5.

Skiles, S. McKenzie, Thomas H. Painter, Jayne Belnap, Lacey Holland, Richard L. Reynolds, Harland L. Goldstein, and John Lin. 2015. "Regional Variability in Dust-on-Snow Processes and Impacts in the Upper Colorado River Basin." Hydrological Processes 29 (26): 5397–5413. https://doi.org/10.1002/hyp.10569.

Skiles, S. McKenzie, Thomas H. Painter, Jeffrey S. Deems, Ann C. Bryant, and Christopher C. Landry. 2012. "Dust Radiative Forcing in Snow of the Upper Colorado River Basin: 2. Interannual Variability in Radiative Forcing and Snowmelt Rates." Water Resources Research 48 (7). https://doi.org/10.1029/2012WR011986.

Slater, Andrew G. 2016. "Surface Solar Radiation in North America: A Comparison of Observations, Reanalyses, Satellite, and Derived Products." Journal of Hydrometeorology 17 (1): 401–20. https://doi.org/10.1175/JHM-D-15-0087.1.

"SMAP/Sentinel-1 L2 Radiometer/Radar 30-Second Scene 3 Km EASE-Grid Soil Moisture, Version 2." 2018. NASA National Snow and Ice Data Center DAAC. https://doi.org/10.5067/ke1csvxmi95y.

Sospedra-Alfonso, Reinel, Joe R. Melton, and William J. Merryfield. 2015. "Effects of Temperature and Precipitation on Snowpack Variability in the Central Rocky Mountains as a Function of Elevation." Geophysical Research Letters 42 (11): 4429–38. https://doi.org/10.1002/2015GL063898.

Srinivas, V. V., and K. Srinivasan. 2005. "Hybrid Moving Block Bootstrap for Stochastic Simulation of Multi-Site Multi-Season Streamflows." Journal of Hydrology 302 (1): 307–30. https://doi.org/10.1016/j.jhydrol.2004.07.011.

Srivastav, Roshan K., and Slobodan P. Simonovic. 2014. "An Analytical Procedure for Multi-Site, Multi-Season Streamflow Generation Using Maximum Entropy Bootstrapping." Environmental Modelling & Software 59 (September): 59–75. https://doi.org/10.1016/j.envsoft.2014.05.005.

Stahle, David W., Edward R. Cook, Malcolm K. Cleaveland, Matthew D. Therrell, David M. Meko, Henri D. Grissino-Mayer, Emma Watson, and Brian H. Luckman. 2000. "Tree-Ring Data Document 16th Century Megadrought over North America." Eos, Transactions American Geophysical Union 81 (12): 121. https://doi.org/10.1029/00EO00076.

Stahle, David W., Falko K. Fye, Edward R. Cook, and R. Daniel Griffin. 2007. "Tree-Ring Reconstructed Megadroughts over North America since a.d. 1300." Climatic Change 83 (1–2): 133–49. https://doi.org/10.1007/s10584-006-9171-x.

Stainforth, David A., Thomas E. Downing, Richard Washington, Ana Lopez, and Mark New. 2007. "Issues in the Interpretation of Climate Model Ensembles to Inform Decisions." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365 (1857): 2163–77. https://doi.org/10.1098/rsta.2007.2073.

Stan, Cristiana, David M. Straus, Jorgen S. Frederiksen, Hai Lin, Eric D. Maloney, and Courtney Schumacher. 2017. "Review of Tropical-Extratropical Teleconnections on Intraseasonal Time Scales: The Subseasonal to Seasonal (S2S) Teleconnection Sub-Project." Reviews of Geophysics 55 (4): 902–37. https://doi.org/10.1002/2016RG000538.

Staschus, Konstantin, and Jerson Kelman. 1988. "Probabilistic Dependable Hydro Capacity: The Benefits of Synthetic Hydrology." In Computerized Decision Support Systems for Water Managers. New York, NY: American Society of Civil Engineers. http://www.kelman.com.br/pdf/probabilistic_dependable/probabilistic%20dependable%20hydro.pdf.

Steinschneider, Scott, Rachel McCrary, Linda O. Mearns, and Casey Brown. 2015. "The Effects of Climate Model Similarity on Probabilistic Climate Projections and the Implications for Local, Risk-Based Adaptation Planning: INTERMODEL CORRELATION AND RISK." Geophysical Research Letters 42 (12): 5014–44. https://doi.org/10.1002/2015GL064529.

Stewart, Iris T., Daniel R. Cayan, and Michael D. Dettinger. 2005. "Changes toward Earlier Streamflow Timing across Western North America." Journal of Climate 18 (8): 1136–55. https://doi.org/10.1175/JCLI3321.1.

Stockton, Charles W. 1975. "Long Term Streamflow Records Reconstructed from Tree-Rings." University of Arizona Press, Tucson.

Stockton, Charles W., and W. R. Boggess. 1979. "Geohydrological Implications of Climate Change on Water Resource Development." Fort Belvoir, VA: U.S. Army Coastal Engineering Research Center.

Stockton, Charles W., and G. C. Jacoby. 1976. "Long-Term Surface-Water Supply and Streamflow Trends in the Upper Colorado River Basin. Lake Powell Research Project Bulletin No. 18, Institute of Geophysics and Planetary Physics." University of California at Los Angeles.

Strachan, Scotty. 2016. "Observing Semi-Arid Ecoclimates across Mountain Gradients in the Great Basin, USA." Dissertation, University of Nevada, Reno.

Strachan, Scotty, and Christopher Daly. 2017. "Testing the Daily PRISM Air Temperature Model on Semiarid Mountain Slopes: Testing PRISM Temperature in Mountains." Journal of Geophysical Research: Atmospheres 122 (11): 5697–5715. https://doi.org/10.1002/2016JD025920.

Stratus Consulting. 2005. "Compendium on Methods and Tools to Evaluate Impacts of, and Vulnerability and Adaptation to, Climate Change-Final Draft Report." UNFCCC Secretariat. https://unfccc.int/files/adaptation/methodologies_for/vulnerability_and_adaptation/application/pdf/consolidated_version_updated_021204.pdf.

Sveinsson, O. G. B., Jose D. Salas, W. L. Lane, and D. K. Frevert. 2007. "Stochastic Analysis, Modeling, and Simulation (SAMS) Version 2007." Manual.

Switanek, Matthew B., and Peter A. Troch. 2011. "Decadal Prediction of Colorado River Streamflow Anomalies Using Ocean-Atmosphere Teleconnections." Geophysical Research Letters 38 (23): n/a-n/a. https://doi.org/10.1029/2011GL049644.

Tapley, Byron D., Bettadpur Srinivas, John C. Ries, Paul F. Thompson, and Michael M. Watkins. 2004. "GRACE Measurements of Mass Variability in the Earth System." Science 305 (5683): 503–5. https://doi.org/10.1126/science.1099192.

Tarboton, David G. 1994. "The Source Hydrology of Severe Sustained Drought in the Southwestern United States." Journal of Hydrology 161 (1–4): 31–69. https://doi.org/10.1016/0022-1694(94)90120-1.

———. 1995. "Hydrologic Scenarios for Severe Sustained Drought in the Southwestern United States." Water Resources Bulletin 35 (5).

Tarboton, David G., Ashish Sharma, and Upmanu Lall. 1998. "Disaggregation Procedures for Stochastic Hydrology Based on Nonparametric Density Estimation." Water Resources Research 34 (1): 107–19. https://doi.org/10.1029/97WR02429.

Tebaldi, Claudia, and Reto Knutti. 2007. "The Use of the Multi-Model Ensemble in Probabilistic Climate Projections." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365 (1857): 2053–75. https://doi.org/10.1098/rsta.2007.2076.

Technical Committee on Standardization of Reference Evapotranspiration. 2005. The ASCE Standardized Reference Evapotranspiration Equation. Edited by Richard G. Allen, Ivan A. Walter, Ronald L. Elliott, Terry A. Howell, Daniel Itenfisu, Marvin E. Jensen, and Richard L. Snyder. Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784408056.

Tessendorf, Sarah A., Jeffrey R. French, Katja Friedrich, Bart Geerts, Robert M. Rauber, Roy M. Rasmussen, Lulin Xue, et al. 2019. "A Transformational Approach to Winter Orographic Weather Modification Research: The SNOWIE Project." Bulletin of the American Meteorological Society 100 (1): 71–92. https://doi.org/10.1175/BAMS-D-17-0152.1.

Texas A&M University. 2019a. "Hydrologic Modeling Inventory Website." TAMU Hydrologic Modeling Inventory. 2019. https://hydrologicmodels.tamu.edu/.

———. 2019b. "Water Rights Analysis Package." 2019. https://ceprofs.civil.tamu.edu/rwurbs/wrap.htm.

Thirel, Guillaume, E. Martin, J.-F. Mahfouf, S. Massart, S. Ricci, and F. Habets. 2010. "A Past Discharges Assimilation System for Ensemble Streamflow Forecasts over France – Part 1: Description and Validation of the Assimilation System." Hydrology and Earth System Sciences 14 (8): 1623–37. https://doi.org/10.5194/hess-14-1623-2010.

Thirel, Guillaume, E. Martin, J.-F. Mahfouf, S. Massart, S. Ricci, F. Regimbeau, and F. Habets. 2010. "A Past Discharge Assimilation System for Ensemble Streamflow Forecasts over France – Part 2: Impact on the Ensemble Streamflow Forecasts." Hydrology and Earth System Sciences 14 (8): 1639–53. https://doi.org/10.5194/hess-14-1639-2010.

Thober, Stephan, Rohini Kumar, Justin Sheffield, Juliane Mai, David Schäfer, and Luis Samaniego. 2015. "Seasonal Soil Moisture Drought Prediction over Europe Using the North American Multi-Model Ensemble (NMME)." Journal of Hydrometeorology 16 (6): 2329–44. https://doi.org/10.1175/JHM-D-15-0053.1.

Thornton, Peter E., Hubert Hasenauer, and Michael A. White. 2000. "Simultaneous Estimation of Daily Solar Radiation and Humidity from Observed Temperature and Precipitation: An Application over Complex Terrain in Austria." Agricultural and Forest Meteorology 104 (4): 255–71. https://doi.org/10.1016/S0168-1923(00)00170-2.

Thornton, Peter E., and Steven W. Running. 1999. "An Improved Algorithm for Estimating Incident Daily Solar Radiation from Measurements of Temperature, Humidity, and Precipitation." Agricultural and Forest Meteorology 93 (4): 211–28. https://doi.org/10.1016/S0168-1923(98)00126-9.

Thornton, Peter E., Steven W. Running, and Michael A. White. 1997. "Generating Surfaces of Daily Meteorological Variables over Large Regions of Complex Terrain." Journal of Hydrology 190 (3–4): 214–51. https://doi.org/10.1016/S0022-1694(96)03128-9.

Thornton, Peter E., M. M. Thornton, B. W. Mayer, Y. Wei, R. Devarakonda, Russell S. Vose, and R. B. Cook. 2016. "Daymet: Daily Surface Weather Data on a 1-Km Grid for North America, Version 3." ORNL DAAC Distributed Active Archive Center for Biogeochemical Dynamics. 2016.

Thrasher, Bridget, Jun Xiong, Weile Wang, Forrest Melton, Andrew Michaelis, and Ramakrishna Nemani. 2013. "Downscaled Climate Projections Suitable for Resource Management." Eos, Transactions American Geophysical Union 94 (37): 321–23. https://doi.org/10.1002/2013EO370002.

Tighi, Shana Goffman. 2006. "Uncertainty Analysis: Mid-Term Operational Model for the Lower Colorado River." Master's, University of Nevada, Las Vegas.

Timm, Oliver Elison, Thomas W. Giambelluca, and Henry F. Diaz. 2015. "Statistical Downscaling of Rainfall Changes in Hawai'i Based on the CMIP5 Global Model Projections: Downscaled Rainfall Changes in Hawai'i." Journal of Geophysical Research: Atmospheres 120 (1): 92–112. https://doi.org/10.1002/2014JD022059.

Tippett, Michael K., Meghana Ranganathan, Michelle L'Heureux, Anthony G. Barnston, and Timothy DelSole. 2017. "Assessing Probabilistic Predictions of ENSO Phase and Intensity from the North American Multimodel Ensemble." Climate Dynamics, May. https://doi.org/10.1007/s00382-017-3721-y.

Tipton, Royce, and Olin Kalmbach. 1965. "Water Supplies of the Colorado River--Available for Use by the States of the Upper Division and for Use from the Main Stem by the States of Arizona, California and Nevada in the Lower Basin." Engineering. Denver, Colorado: Upper Colorado River Commission. https://wwa.colorado.edu/resources/colorado-river/docs/management/Tipton1965.pdf.

Tokarska, Katarzyna B., Martin B. Stolpe, Sebastian Sippel, Erich M. Fischer, Christopher J. Smith, Flavio Lehner, and Reto Knutti. 2020. "Past Warming Trend Constrains Future Warming in CMIP6 Models." Science Advances 6 (12). https://doi.org/10.1126/sciadv.aaz9549.

Tolson, B. A., and C. A. Shoemaker. 2006. "The Dynamically Dimensioned Search (DDS) Algorithm as a Robust Optimization Tool in Hydrologic Modeling." In AGU Fall Meeting Abstracts, 41:H41I-07. http://adsabs.harvard.edu/abs/2006AGUFM.H41I..07T.

Tootle, Glenn A., Singh Ashok K., Thomas C. Piechota, and Farnham Irene. 2007. "Long Lead-Time Forecasting of U.S. Streamflow Using Partial Least Squares Regression." Journal of Hydrologic Engineering 12 (5): 442–51. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:5(442).

Topping, David J., John C. Schmidt, and L.E. Vierra Jr. 2003. "Computation and Analysis of the Instantaneous-Discharge Record for the Colorado River at Lees Ferry, Arizona : May 8, 1921, through September 30, 2000." USGS Numbered Series 1677. Professional Paper. Reston, VA: U.S. Geological Survey. http://pubs.er.usgs.gov/publication/pp1677.

Tourre, Yves M., Balaji Rajagopalan, Yochanan Kushnir, Mathew Barlow, and Warren B. White. 2001. "Patterns of Coherent Decadal and Interdecadal Climate Signals in the Pacific Basin during the 20th Century." Geophysical Research Letters 28 (10): 2069–72. https://doi.org/10.1029/2000GL012780.

Towler, Erin, Debasish PaiMazumder, and James Done. 2018. "Toward the Application of Decadal Climate Predictions." Journal of Applied Meteorology and Climatology 57 (3): 555–68. https://doi.org/10.1175/JAMC-D-17-0113.1.

Udall, Bradley, and Jonathan Overpeck. 2017. "The Twenty-First Century Colorado River Hot Drought and Implications for the Future." Water Resources Research 53 (3): 2404–18. https://doi.org/10.1002/2016WR019638.

URS. 2013. "Assessing Agricultural Consumptive Use in the Upper Colorado River Basin - Phase I." http://www.ucrcommission.com/RepDoc/Studies/Assessing%20_Ag_CU_PhaseI.pdf.

———. 2016. "Assessing Agricultural Consumptive Use in the Upper Colorado River Basin - Phase II." http://www.ucrcommission.com/RepDoc/Studies/Assessing%20_Ag_CU_PhaseII.pdf.

US Army Corps of Engineers. 1971. "HEC-4 Monthly Streamflow Simulation User's Manual." United States Army Corps of Engineers, Department of Hydrologic Engineering Center. https://www.hec.usace.army.mil/publications/ComputerProgramDocumentation/HEC-4_UsersManual_(CPD-4).pdf.

———. 2012. "HEC-ResPRM." 2012. https://www.hec.usace.army.mil/software/hec-resprm/.

US Geological Survey. 1977. "Water Resources Data for Colorado, Water Year 1975. Volume 2, Colorado River Basin." U.S. GEOLOGICAL SURVEY WATER-DATA REPORT CO-75-2. U.S. Geological Survey.

———. 2018a. "Federal Priorities Streamgages (FPS) Mapper." 2018. https://water.usgs.gov/networks/fps/.

———. 2018b. "USGS Water-Year Summary for Site 09315000." 2018. https://waterdata.usgs.gov/nwis/wys_rpt/?site_no=09315000.

———. 2018c. "USGS Water-Year Summary for Site 09380000." 2018. https://waterdata.usgs.gov/nwis/wys_rpt/?site_no=09380000&agency_cd=USGS.

———. n.d. "Water Resources of the United States—Annual Water Data Report—Documentation." Annual Water Data Report. Accessed March 21, 2019. https://wdr.water.usgs.gov/current/documentation.html.

U.S. Secretary of the Interior. 2007. "Record of Decision Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead." U.S. Department of the Interior. https://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf.

USGCRP. 2017. "Climate Science Special Report: Fourth National Climate Assessment, Volume I." Washington, D.C.: U.S Global Change Research Program. doi: 10.7930/J0J964J6.

Van den Dool, Huug M. 1994. "Searching for Analogues, How Long Must We Wait?" Tellus A 46 (3): 314–24. https://doi.org/10.1034/j.1600-0870.1994.t01-2-00006.x.

———. 2003. "Performance and Analysis of the Constructed Analogue Method Applied to U.S. Soil Moisture over 1981–2001." Journal of Geophysical Research 108 (D16): 8617. https://doi.org/10.1029/2002JD003114.

———. 2007. Empirical Methods in Short-Term Climate Prediction. Oxford ; New York: Oxford University Press.

Vano, Julie A., Jeffrey R. Arnold, Bart Nijssen, Martyn P. Clark, Andrew W. Wood, Ethan D. Gutmann, Nans Addor, Joseph Hamman, and Flavio Lehner. 2018. "DOs and DON'Ts for Using Climate Change Information for Water Resource Planning and Management: Guidelines for Study Design." Climate Services 12 (December): 1–13. https://doi.org/10.1016/j.cliser.2018.07.002.

Vano, Julie A., Tapash Das, and Dennis P. Lettenmaier. 2012. "Hydrologic Sensitivities of Colorado River Runoff to Changes in Precipitation and Temperature*." Journal of Hydrometeorology 13 (3): 932–49. https://doi.org/10.1175/JHM-D-11-069.1.

Vano, Julie A., and Dennis P. Lettenmaier. 2014. "A Sensitivity-Based Approach to Evaluating Future Changes in Colorado River Discharge." Climatic Change 122 (4): 621–34. https://doi.org/10.1007/s10584-013-1023-x.

Vano, Julie A., Bradley Udall, Daniel R. Cayan, Jonathan T. Overpeck, Levi D. Brekke, Tapash Das, Holly C. Hartmann, et al. 2014. "Understanding Uncertainties in Future Colorado River Streamflow." Bulletin of the American Meteorological Society 95 (1): 59–78. https://doi.org/10.1175/BAMS-D-12-00228.1.

Verdin, Andrew, Balaji Rajagopalan, William Kleiber, Guillermo Podestá, and Federico Bert. 2018. "A Conditional Stochastic Weather Generator for Seasonal to Multi-Decadal Simulations." Journal of Hydrology 556 (January): 835–46. https://doi.org/10.1016/j.jhydrol.2015.12.036.

Vigaud, N., Andrew W. Robertson, and M. K. Tippett. 2017. "Multimodel Ensembling of Subseasonal Precipitation Forecasts over North America." Monthly Weather Review 145 (10): 3913–28. https://doi.org/10.1175/MWR-D-17-0092.1.

Vliet, Michelle T. H. van, David Wiberg, Sylvain Leduc, and Keywan Riahi. 2016. "Power-Generation System Vulnerability and Adaptation to Changes in Climate and Water Resources." Nature Climate Change 6 (4): 375–80. https://doi.org/10.1038/nclimate2903.

Vogel, Jason M. 2015. "Actionable Science in Practice: Co-Producing Climate Change Information for Water Utility Vulnerability Assessments." Water Utility Climate Alliance.

Vogel, Richard M. 2017. "Stochastic Watershed Models for Hydrologic Risk Management." Water Security 1 (July): 28–35. https://doi.org/10.1016/j.wasec.2017.06.001.

Vose, Russell S., Scott Applequist, Mike Squires, Imke Durre, Matthew J. Menne, Claude N. Williams, Chris Fenimore, Karin Gleason, and Derek Arndt. 2014. "Improved Historical Temperature and Precipitation Time Series for U.S. Climate Divisions." Journal of Applied Meteorology and Climatology 53 (5): 1232–51. https://doi.org/10.1175/JAMC-D-13-0248.1.

Vuuren, Detlef P. van, Jae Edmonds, Mikiko Kainuma, Keywan Riahi, Allison Thomson, Kathy Hibbard, George C. Hurtt, et al. 2011. "The Representative Concentration Pathways: An Overview." Climatic Change 109 (1–2): 5–31. https://doi.org/10.1007/s10584-011-0148-z.

Walton, Daniel, and Alex Hall. 2018. "An Assessment of High-Resolution Gridded Temperature Datasets over California." Journal of Climate 31 (10): 3789–3810. https://doi.org/10.1175/JCLI-D-17-0410.1.

Wang, Q. J., D. E. Robertson, and F. H. S. Chiew. 2009. "A Bayesian Joint Probability Modeling Approach for Seasonal Forecasting of Streamflows at Multiple Sites." Water Resources Research 45 (5). https://doi.org/10.1029/2008WR007355.

Wang, Shih-Yu, Robert R. Gillies, Oi-Yu Chung, and Chaopeng Shen. 2018. "Cross-Basin Decadal Climate Regime Connecting the Colorado River with the Great Salt Lake." Journal of Hydrometeorology 19 (4): 659–65. https://doi.org/10.1175/JHM-D-17-0081.1.

Wang, Shih-Yu, Robert R. Gillies, Lawrence E. Hipps, and Jiming Jin. 2011. "A Transition-Phase Teleconnection of the Pacific Quasi-Decadal Oscillation." Climate Dynamics 36 (3–4): 681–93. https://doi.org/10.1007/s00382-009-0722-5.

Waring, R. H., N. C. Coops, W. Fan, and J. M. Nightingale. 2006. "MODIS Enhanced Vegetation Index Predicts Tree Species Richness across Forested Ecoregions in the Contiguous U.S.A." Remote Sensing of Environment 103 (2): 218–26. https://doi.org/10.1016/j.rse.2006.05.007.

Water Resources and Climate Change Workgroup. 2016. "Looking Forward: Priorities for Managing Freshwater Resources in a Changing Climate." Interagency Climate Change Adaptation Task Force.

Waugh, Darryn W., Adam H. Sobel, and Lorenzo M. Polvani. 2017. "What Is the Polar Vortex and How Does It Influence Weather?" Bulletin of the American Meteorological Society 98 (1): 37–44. https://doi.org/10.1175/BAMS-D-15-00212.1.

Weerts, Albrecht H., Ghada Y. El Serafy, Stef Hummel, Juzer Dhondia, and Herman Gerritsen. 2010. "Application of Generic Data Assimilation Tools (DATools) for Flood Forecasting Purposes." Computers & Geosciences 36 (4): 453–63. https://doi.org/10.1016/j.cageo.2009.07.009.

Weisbecker, Leo. 1974. Snowpack, Cloud-Seeding, and the Colorado River: A Technology Assessment of Weather Modification. University of Oklahoma Press.

Weisheimer, A., and T. N. Palmer. 2014. "On the Reliability of Seasonal Climate Forecasts." Journal of The Royal Society Interface 11 (96): 20131162. https://doi.org/10.1098/rsif.2013.1162.

Welles, Edwin, and Soroosh Sorooshian. 2009. "Scientific Verification of Deterministic River Stage Forecasts." Journal of Hydrometeorology 10 (2): 507–20. https://doi.org/10.1175/2008JHM1022.1.

Welles, Edwin, Soroosh Sorooshian, Gary Carter, and Billy Olsen. 2007. "Hydrologic Verification: A Call for Action and Collaboration." Bulletin of the American Meteorological Society 88 (4): 503–12. https://doi.org/10.1175/BAMS-88-4-503.

Werner, Kevin, David Brandon, Martyn P. Clark, and Subhrendu Gangopadhyay. 2004. "Climate Index Weighting Schemes for NWS ESP-Based Seasonal Volume Forecasts." Journal of Hydrometeorology 5 (6): 1076–90. https://doi.org/10.1175/JHM-381.1.

———. 2005. "Incorporating Medium-Range Numerical Weather Model Output into the Ensemble Streamflow Prediction System of the National Weather Service." Journal of Hydrometeorology 6 (2): 101–14. https://doi.org/10.1175/JHM411.1.

Western Regional Climate Center. n.d. "RAWS USA Climate Archive." RAWS USA Climate Archive.

Westrick, Kenneth J., Pascal Storck, and Clifford F. Mass. 2002. "Description and Evaluation of a Hydrometeorological Forecast System for Mountainous Watersheds." Weather and Forecasting 17 (2): 250–62. https://doi.org/10.1175/1520-0434(2002)017<0250:DAEOAH>2.0.CO;2.

Wetterhall, F., and F. Di Giuseppe. 2018. "The Benefit of Seamless Forecasts for Hydrological Predictions over Europe." Hydrol. Earth Syst. Sci. 22 (6): 3409–20. https://doi.org/10.5194/hess-22-3409-2018.

Wheeler, Kevin G., David E. Rosenberg, and John C. Schmidt. 2019. "Water Resource Modeling of the Colorado River: Present and Future Strategies," 47.

Wilby, Robert L., C. W. Dawson, and E. M. Barrow. 2002. "SDSM — a Decision Support Tool for the Assessment of Regional Climate Change Impacts." Environmental Modelling & Software 17 (2): 145–57. https://doi.org/10.1016/S1364-8152(01)00060-3.

Wilby, Robert L., and T. M. L. Wigley. 1997. "Downscaling General Circulation Model Output: A Review of Methods and Limitations." Progress in Physical Geography: Earth and Environment 21 (4): 530–48. https://doi.org/10.1177/030913339702100403.

Wilby, Robert L., Hany Hassan, and Keisuke Hanaki. 1998. "Statistical Downscaling of Hydrometeorological Variables Using General Circulation Model Output." Journal of Hydrology 205 (1–2): 1–19. https://doi.org/10.1016/S0022-1694(97)00130-3.

Williams, Mark W., Eran Hood, Noah P. Molotch, Nel Caine, Rory Cowie, and Fengjing Liu. 2015. "The 'Teflon Basin' Myth: Hydrology and Hydrochemistry of a Seasonally Snow-Covered Catchment." Plant Ecology & Diversity 8 (5–6): 639–61. https://doi.org/10.1080/17550874.2015.1123318.

Wilson, Rob, Edward Cook, Rosanne D'Arrigo, Nadja Riedwyl, Michael N. Evans, Alexander Tudhope, and Rob Allan. 2010. "Reconstructing ENSO: The Influence of Method, Proxy Data, Climate Forcing and Teleconnections." Journal of Quaternary Science 25 (1): 62–78. https://doi.org/10.1002/jqs.1297.

Wise, Erika K. 2010. "Spatiotemporal Variability of the Precipitation Dipole Transition Zone in the Western United States." Geophysical Research Letters 37 (7): n/a-n/a. https://doi.org/10.1029/2009GL042193.

———. 2015. "Tropical Pacific and Northern Hemisphere Influences on the Coherence of Pacific Decadal Oscillation Reconstructions." International Journal of Climatology 35 (1): 154–60. https://doi.org/10.1002/joc.3966.

Wisser, Dominik, Steve Frolking, Ellen M. Douglas, Balazs M. Fekete, Charles J. Vörösmarty, and Andreas H. Schumann. 2008. "Global Irrigation Water Demand: Variability and Uncertainties Arising from Agricultural and Climate Data Sets." Geophysical Research Letters 35 (24). https://doi.org/10.1029/2008GL035296.

Wolter, Klaus. 2002. "Climate Projections: Assessing Water Year (WY) 2002 Forecasts and Developing WY 2003 Forecasts." CWRRI Information Series Report. Fort Collins, Colorado: Colorado Water Resources Research Institute.

Wolter, Klaus, Randall Dole, and Catherine A. Smith. 1999. "Short-Term Climate Extremes over the Continental U.S. and ENSO. Part I: Seasonal Temperatures." Journal of Climate 12: 3255–72. https://doi.org/10.1175/1520-0442(1999)012<3255:STCEOT>2.0.CO;2.

Wolter, Klaus, and Michael S. Timlin. 2011. "El Niño/Southern Oscillation Behaviour since 1871 as Diagnosed in an Extended Multivariate ENSO Index (MEI.Ext)." International Journal of Climatology 31 (7): 1074–87. https://doi.org/10.1002/joc.2336.

Wood, Andrew W., L. Ruby Leung, V. Sridhar, and Dennis P. Lettenmaier. 2004. "Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs." Climatic Change 62 (1–3): 189–216. https://doi.org/10.1023/B:CLIM.0000013685.99609.9e.

Wood, Andrew W. 2008. "The University of Washington Surface Water Monitor: An Experimental Platform for National Hydrologic Assessment and Prediction." Proceedings of the AMS 22nd Conference on Hydrology, New Orleans. http://www.hydro.washington.edu/forecast/monitor/info/Wood_SWMonitor_AMS08.pdf.

Wood, Andrew W., S. Arumugam, and Pablo A. Mendoza. 2018. "The Post-Processing of Seasonal Streamflow Forecasts, Chapter 7.3 in the Handbook of Hydrometeorological Ensemble Forecasting." In Handbook of Hydrometeorological Ensemble Forecasting. Springer-Verlag GmbH, Berlin Heidelberg. https://link.springer.com/referenceworkentry/10.1007/978-3-642-40457-3_37-2.

Wood, Andrew W., Arun Kumar, and Dennis P. Lettenmaier. 2005. "A Retrospective Assessment of National Centers for Environmental Prediction Climate Model–Based Ensemble Hydrologic Forecasting in the Western United States." Journal of Geophysical Research: Atmospheres 110 (D4). https://doi.org/10.1029/2004JD004508.

Wood, Andrew W., and Dennis P. Lettenmaier. 2006. "A Test Bed for New Seasonal Hydrologic Forecasting Approaches in the Western United States." Bulletin of the American Meteorological Society 87 (12): 1699–1712. https://doi.org/10.1175/BAMS-87-12-1699.

Wood, Andrew W., Edwin P. Maurer, Arun Kumar, and Dennis P. Lettenmaier. 2002. "Long-Range Experimental Hydrologic Forecasting for the Eastern United States." Journal of Geophysical Research: Atmospheres 107 (D20): ACL 6-1-ACL 6-15. https://doi.org/10.1029/2001JD000659.

Wood, Andrew W., Thomas C. Pagano, Maury Roos, and Michael Anderson. 2016. "Tracing the Origins of ESP: HEPEX Historical Hydrology Series, Edition 1." HEPEX (blog). April 26, 2016. https://hepex.irstea.fr/tracing-the-origins-of-esp/.

Wood, Andrew W., and John C. Schaake. 2008. "Correcting Errors in Streamflow Forecast Ensemble Mean and Spread." Journal of Hydrometeorology 9 (1): 132–48. https://doi.org/10.1175/2007JHM862.1.

Wood, Eric F., Joshua K. Roundy, Tara J. Troy, Rens van Beek, Marc Bierkens, Eleanor Blyth, Ad de Roo, et al. 2012. "Reply to Comment by Keith J. Beven and Hannah L. Cloke on 'Hyperresolution Global Land Surface Modeling: Meeting a Grand Challenge for Monitoring Earth's Terrestrial Water.'" Water Resources Research 48 (1). https://doi.org/10.1029/2011WR011202.

Woodbury, M., M. Baldo, D. Yates, and L. Kaatz. 2012. "Joint Front Range Climate Change Vulnerability Study." Denver: Water Research Foundation.

Woodhouse, Connie A. 2003. "A 431-Yr Reconstruction of Western Colorado Snowpack from Tree Rings." Journal of Climate 16: 11.

———. 2012. "A Catalogue of 20th and 21st Century Droughts for the Upper Colorado River Basin." Bureau of Reclamation, Lower Colorado Region. https://cwoodhouse.faculty.arizona.edu/content/catalogue-20th-and-21st-century-droughts-upper-colorado-river-basin.

Woodhouse, Connie A., Stephen T. Gray, and David M. Meko. 2006. "Updated Streamflow Reconstructions for the Upper Colorado River Basin." Water Resources Research 42 (5). https://doi.org/10.1029/2005WR004455.

Woodhouse, Connie A., Kenneth E. Kunkel, David R. Easterling, and Edward R. Cook. 2005. "The Twentieth-Century Pluvial in the Western United States." Geophysical Research Letters 32 (7): n/a-n/a. https://doi.org/10.1029/2005GL022413.

Woodhouse, Connie A., and Jeffrey J. Lukas. 2006. "Drought, Tree Rings and Water Resource Management in Colorado." Canadian Water Resources Journal 31 (4): 297–310. https://doi.org/10.4296/cwrj3104297.

Woodhouse, Connie A., Jeffrey J. Lukas, Kiyomi Morino, David M. Meko, and Katherine K. Hirschboeck. 2016. "Using the Past to Plan for the Future— the Value of Paleoclimate Reconstructions for Water Resource Planning." In Water Policy and Planning in a Variable and Changing Climate. Drought and Water Crises. CRC Press. https://doi.org/10.1201/b19534.

Woodhouse, Connie A., David M. Meko, Glen M. MacDonald, Dave W. Stahle, and Edward R. Cook. 2010. "A 1,200-Year Perspective of 21st Century Drought in Southwestern North America." Proceedings of the National Academy of Sciences 107 (50): 21283–88. https://doi.org/10.1073/pnas.0911197107.

Woodhouse, Connie A., and Jonathan T. Overpeck. 1998. "2000 Years of Drought Variability in the Central United States." Bulletin of the American Meteorological Society 79 (12): 2693–2714. https://doi.org/10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2.

Woodhouse, Connie A., and Gregory T. Pederson. 2018. "Investigating Runoff Efficiency in Upper Colorado River Streamflow over Past Centuries." Water Resources Research 54 (1): 286–300. https://doi.org/10.1002/2017WR021663.

Woodhouse, Connie A., Gregory T. Pederson, Kiyomi Morino, Stephanie A. McAfee, and Gregory J. McCabe. 2016. "Increasing Influence of Air Temperature on Upper Colorado River Streamflow." Geophysical Research Letters 43 (5): 2174–81. https://doi.org/10.1002/2015GL067613.

World Meteorological Organization. 2008. Guide to Meteorological Instruments and Methods of Observation. Geneva, Switzerland: World Meteorological Organization.

———. 2013. "Sub-Seasonal to Seasonal Prediction Research Implementation Plan." Geneva. http://s2sprediction.net/static/documents.

———. 2017. "Coupled Data Assimilation for Integrated Earth System Analysis and Prediction: Goals, Challengesand Recommendations." WWRP 2017-3. https://www.wmo.int/pages/prog/arep/wwrp/new/documents/Final_WWRP_2017_3_27_July.pdf .

Wu, Limin, Dong-Jun Seo, Julie Demargne, James D. Brown, Shuzheng Cong, and John C. Schaake. 2011. "Generation of Ensemble Precipitation Forecast from Single-Valued Quantitative Precipitation Forecast for Hydrologic Ensemble Prediction." Journal of Hydrology 399 (3–4): 281–98. https://doi.org/10.1016/j.jhydrol.2011.01.013.

Wurbs, Ralph. 1994. "Computer Models for Water Resources Planning and Management." IWR Report 94-NDS-7. Institute for Water Resources, US Army Corps of Engineers. https://apps.dtic.mil/dtic/tr/fulltext/u2/a295807.pdf.

———. 2012. "Reservoir/River System Management Models." Texas Water Journal 3 (1): 16.

Xia, Youlong, Kenneth Mitchell, Michael Ek, Justin Sheffield, Brian Cosgrove, Eric Wood, Lifeng Luo, et al. 2012. "Continental-Scale Water and Energy Flux Analysis and Validation for the North American Land Data Assimilation System Project Phase 2 (NLDAS-2): 1. Intercomparison and Application of Model Products." Journal of Geophysical Research: Atmospheres 117 (D3): n/a-n/a. https://doi.org/10.1029/2011JD016048.

Xiao, Mu, Bradley Udall, and Dennis P. Lettenmaier. 2018. "On the Causes of Declining Colorado River Streamflows." Water Resources Research 54 (9): 6739–56. https://doi.org/10.1029/2018WR023153.

Yang, Daqing, Barry E. Goodison, Shig Ishida, and Carl S. Benson. 1998. "Adjustment of Daily Precipitation Data at 10 Climate Stations in Alaska: Application of World Meteorological Organization Intercomparison Results." Water Resources Research 34 (2): 241–56. https://doi.org/10.1029/97WR02681.

Yapo, Patrice Ogou, Hoshin Vijai Gupta, and Soroosh Sorooshian. 1998. "Multi-Objective Global Optimization for Hydrologic Models." Journal of Hydrology 204 (1): 83–97. https://doi.org/10.1016/S0022-1694(97)00107-8.

Yaseen, Zaher Mundher, Ahmed El-shafie, Othman Jaafar, Haitham Abdulmohsin Afan, and Khamis Naba Sayl. 2015. "Artificial Intelligence Based Models for Stream-Flow Forecasting: 2000–2015." Journal of Hydrology 530 (November): 829–44. https://doi.org/10.1016/j.jhydrol.2015.10.038.

Yeager, Stephen G., G. Danabasoglu, N. A. Rosenbloom, W. Strand, S. C. Bates, G. A. Meehl, A. R. Karspeck, et al. 2018. "Predicting Near-Term Changes in the Earth System: A Large Ensemble of Initialized Decadal Prediction Simulations Using the Community Earth System Model." Bulletin of the American Meteorological Society 99 (9): 1867–86. https://doi.org/10.1175/BAMS-D-17-0098.1.

Yu, Jin-Yi, and Yuhao Zou. 2013. "The Enhanced Drying Effect of Central-Pacific El Niño on US Winter." Environmental Research Letters 8 (1): 014019. https://doi.org/10.1088/1748-9326/8/1/014019.

Yuan, Xing, Eric F. Wood, Joshua K. Roundy, and Ming Pan. 2013. "CFSv2-Based Seasonal Hydroclimatic Forecasts over the Conterminous United States." Journal of Climate 26 (13): 4828–47. https://doi.org/10.1175/JCLI-D-12-00683.1.

Zachariassen, John, Karl F. Zeller, Ned Nikolov, and Tom McClelland. 2003. "A Review of the Forest Service Remote Automated Weather Station (RAWS) Network." RMRS-GTR-119. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-119.

Zagona, Edith, Terrance J. Fulp, Richard Shane, Timothy Magee, and H. Morgan Goranflo. 2001. "Riverware: A Generalized Tool for Complex Reservoir System Modeling." JAWRA Journal of the American Water Resources Association 37 (4): 913–29. https://doi.org/10.1111/j.1752-1688.2001.tb05522.x.

Zagona, Edith. 2010. "Riverware's Integrated Modeling and Analysis Tools for Long-Term Planning under Uncertainty," 12.

Zeng, Xubin, Patrick Broxton, and Nicholas Dawson. 2018. "Snowpack Change from 1982 to 2016 over Conterminous United States." Geophysical Research Letters, December. https://doi.org/10.1029/2018GL079621.

Zhang, Chidong. 2013. “Madden–Julian Oscillation: Bridging Weather and Climate.” Bulletin of the American Meteorological Society 94 (12): 1849–70. https://doi.org/10.1175/BAMS-D-12-00026.1.

Zhang, Lanhui, Chansheng He, Mingmin Zhang, and Yi Zhu. 2019. “Evaluation of the SMOS and SMAP Soil Moisture Products under Different Vegetation Types against Two Sparse in Situ Networks over Arid Mountainous Watersheds, Northwest China.” Science China Earth Sciences 62 (4): 703–18. https://doi.org/10.1007/s11430-018-9308-9.

Zhao, R. J., Y. L. Zhang, L. R. Fang, X. R. Liu, and Q. S. Zhang. 1980. “The Xinanjiang Model.” In Hydrological Forecasting Proceedings Oxford Symposium, 129:351–56.

Zhou, Shuntai, Michelle L’Heureux, Scott Weaver, and Arun Kumar. 2012. “A Composite Study of the MJO Influence on the Surface Air Temperature and Precipitation over the Continental United States.” Climate Dynamics 38 (7–8): 1459–71. https://doi.org/10.1007/s00382-011-1001-9.

Glossary

ablation
The loss of snow from the snowpack due to melting, evaporation, or wind.

absolute error
The difference between the measured and actual values of *x*.

albedo
The percentage of incoming light that is reflected off of a surface.

aleatory uncertainty
Uncertainty due to randomness in the behavior of a system (i.e., natural variability)

anomaly
A deviation from the expected or normal value.

atmospheric river (AR)
A long and concentrated plume of low-level (<5,000’) moisture originating in the tropical Pacific.

autocorrelation
Correlation between consecutive values of the same time series, typically due to time-dependencies in the dataset.

bank storage
Water that seeps into and out of the bed and banks of a stream, lake, or reservoir depending on relative water levels.

bias correction
Adjustments to raw model output (e.g., from a climate model, or streamflow forecast model) using observations in a reference period.

boundary conditions
Conditions that govern the evolution of climate for a given area (e.g., ocean heat flux, soil moisture, sea-ice and snowpack conditions) and can help forecast the future climate state when included in a model.

calibration
The process of comparing a model with the real system, followed by multiple revisions and comparisons so that the model outputs more closely resemble outcomes in the real system.

climate forcing
A factor causing a difference between the incoming and outgoing energy of the Earth’s climate system, e.g., increases in greenhouse-gas concentrations.

climatology
In forecasting and modeling, refers to the historical average climate used as a baseline (e.g., “compared to climatology”). Synonymous with climate normal.

coefficient of variation (CV)
A common measure of variability in a dataset; the standard deviation divided by the mean.

consumptive use
The amount of diverted water that is lost during usage via evapotranspiration, evaporation, or seepage and is thus unavailable for subsequent use.

convection
The vertical transport of heat and moisture in the atmosphere, typically due to an air parcel rising if it is warmer than the surrounding atmosphere.

covariate
A variable (e.g., temperature) whose value changes when the variable under study changes (e.g., precipitation).

cross-correlation
A method for estimating to what degree two variables or datasets are correlated.

cumulative distribution function (CDF)
A function describing the probability that a random variable, such as streamflow, is less than or equal to a specified value. CDF-based probabilities are often expressed in terms of percent exceedance or non-exceedance.

Darcy's Law
The mathematical expression that describes fluid flow through a porous medium (e.g., soil).

datum
The base, or 0.0-foot gage-height (stage), for a stream gage.

dead pool
The point at which the water level of a lake or reservoir is so low, water can no longer be discharged or released downstream.

deterministic
Referring to a system or model in which a given input always produces the same output; the input strictly determines the output.

dewpoint
The local temperature that the air would need to be cooled to (assuming atmospheric pressure and moisture content are constant) in order to achieve a relative humidity (RH) of 100%.

dipole
A pair of two equal and opposing centers of action, usually separated by a distance.

discharge
Volume of water flowing past a given point in the stream in a given period of time; synonymous with streamflow.

distributed
In hydrologic modeling, a distributed model explicitly accounts for spatial variability by dividing basins into grid cells. Contrast with **lumped** model.

downscaling
Method to take data at coarse scales, e.g., from a GCM, and translate those data to more local scales.

dynamical
In modeling, refers to the use of a physical model, i.e., basic physical equations represent some or most of the relevant processes.

environmental flow
Water that is left in or released into a river to manage the quantity, quality, and timing of flow in order to sustain the river's ecosystem.

epistemic uncertainty
Uncertainty due to incomplete knowledge of the behavior of a system.

evapotranspiration
A combination of evaporation from the land surface and water bodies, and transpiration of water from plant surfaces to the atmosphere. Generally includes sublimation from the snow surface as well.

fixed lapse rate
A constant rate of change of an atmospheric variable, usually temperature, with elevation.

flow routing
The process of determining the flow hydrograph at sequential points along a stream based on a known hydrograph upstream.

forcing - see **climate forcing or weather forcing**

forecast
A prediction of future hydrologic or climate conditions based on the initial (current) conditions and factors known to influence the evolution of the physical system.

Gaussian filter
A mathematical filter used to remove noise and emphasize a specific frequency of a signal; uses a bell-shaped statistical distribution.

gridded data
Data that is represented in a two-dimensional gridded matrix of graphical contours, interpolated or otherwise derived from a set of point observations.

heat flux
The rate of heat energy transfer from one surface or layer of the atmosphere to the next.

hindcast
A forecast run for a past date or period, using the same model version as for real-time forecasts; used for model calibration and to "spin up" forecast models. Same as **reforecast**.

hydraulic conductivity
A measure of the ease with which water flows through a medium, such as soil or sediment.

hydroclimate
The aggregate of climatic and hydrologic processes and characteristics, and linkages between them, for a watershed or region.

hydrograph
A graph of the volume of water flowing past a location per unit time.

hydrometeorology
A branch of meteorology and hydrology that studies the transfer of water and energy between the land surface and the lower atmosphere.

imaging spectrometer
An instrument used for measuring wavelengths of light spectra in order to create a spectrally-resolved image of an object or area.

in situ
Referring to a ground-based measurement site that is fixed in place.

inhomogeneity
A change in the mean or variance of a time-series of data (such as weather observations) that is caused by changes in the observing station or network, not in the climate itself.

Interim Guidelines
The Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, signed by the Secretary of the Interior in December 2007. The guidelines expire in 2026. https://www.usbr.gov/lc/region/programs/strategies.html

internal variability
Variability in climate that comes from chaotic and unpredictable fluctuations of the Earth's oceans and atmosphere.

interpolation
The process of calculating the value of a function or set of data between two known values.

isothermal
A dynamic in which temperature remains constant while other aspects of the system change.

jet stream
A narrow band of very strong winds in the upper atmosphere that follows the boundary between warmer and colder air masses.

kriging
A smoothing technique that calculates minimum error-variance estimates for unsampled values.

kurtosis
A measure of the sharpness of the peak of a probability distribution.

lag-1 autocorrelation
Serial correlation between data values at adjacent time steps.

lapse rate
The rate of change of an atmospheric variable, such as temperature, with elevation. A lapse rate is adiabatic when no heat exchange occurs between the given air parcel and its surroundings.

latency
The lag, relative to real-time, for producing and releasing a dataset that represents real-time conditions.

latent heat flux
The flow of heat from the Earth's surface to the atmosphere that involves evaporation and condensation of water; the energy absorbed/released during a phase change of a substance.

Law of the River
A collection of compacts, federal laws, court decisions and decrees, contracts, and regulatory guidelines that apportions the water and regulates the use and management of the Colorado River among the seven basin states and Mexico.

LiDAR (or lidar)
Light detection and ranging; a remote sensing method which uses pulsed lasers of light to measure the variable distances from the sensor to the land surface.

longwave radiation
Infrared energy emitted by the Earth and its atmosphere at wavelengths between about 5 and 25 micrometers.

Lower Basin
The portions of the Colorado River Basin in Arizona, California, Nevada, New Mexico and Utah that are downstream of the Colorado River Compact point at Lee Ferry, Arizona.

lumped model
In hydrologic modeling, a lumped model represents individual sub-basins or elevation zones as a single unit, averaging spatial characteristics across that unit. Contrast with **distributed model.**

Markov chain
A mathematical system in which transitions from one state to another are dependent on the current state and time elapsed.

megadrought
A sustained and widespread drought that lasts at least 10-15 years, though definitions in the literature have varied.

metadata
Data that gives information about other data or describes its own dataset.

mid-latitude cyclone
A large (~500-2000 km) storm system that has a low-pressure center, cyclonic (counter-clockwise) flow, and a cold front. Over the western U.S., mid-latitude cyclones almost always move from west to east and are effective at producing precipitation over broad areas.

Minute 319
The binding agreement signed in 2012 by the International Boundary and Water Commission, United States and Mexico, to advance the 1944 Water Treaty between both countries and establish better basin operations and water allocation, and humanitarian measures.

Modoki
An El Niño event that has its warmest SST anomalies located in the central equatorial Pacific; same as "CP" El Niño.

multicollinearity
A condition in which multiple explanatory variables that predict variation in a response variable are themselves correlated with each other.

multiple linear regression
A form of regression in which a model is created by fitting a linear equation over the observed data, typically for two or more explanatory (independent) variables and a response (dependent) variable.

multivariate
Referring to statistical methods in which there are multiple response (dependent) variables being examined.

natural flow
Gaged flow that has been adjusted to remove the effects of upstream human activity such as storage or diversion. Equivalent to **naturalized flow**, **virgin flow**, and **undepleted flow**.

naturalized flow – see ***natural flow***

nearest neighbor method
A nonparametric method that examines the distances between a data point (e.g., a sampled value) and the closest data points to it in *x-y* space ("nearest neighbors," e.g., historical values) and thereby obtains either a classification for the data point (such as wet, dry, or normal) or a set of nearest neighbors (i.e., K-NN).

nonparametric
A statistical method that assumes no underlying mathematical function for a sample of observations.

orographic lift
A process in which air is forced to rise and subsequently cool due to physical barriers such as hills or mountains. This mechanism leads to increased condensation and precipitation over higher terrain.

p
A statistical hypothesis test; the probability of obtaining a particular result purely by chance; a test of statistical significance.

paleohydrology
The study of hydrologic events and processes prior to the instrumental (gaged) record, typically using environmental proxies such as tree rings.

parameterized
Referring to a key variable or factor that is represented in a model by an estimated value (**parameter**) based on observations, rather than being explicitly modeled through physical equations.

parametric
A statistical method that assumes an underlying mathematical function, specified by a set of characteristics, or parameters (e.g., mean and standard deviation) for a sample of observations.

persistence
In hydrology, the tendency of high flows to follow high flows, and low flows to follow low flows. Hydrologic time series with persistence are **autocorrelated**.

phreatophytes
Plants with deep root systems that are dependent on water from the water table or adjacent soil moisture reserves.

pluvial
An extended period, typically 5 years or longer, of abnormally wet conditions; the opposite of drought.

principal components regression (PCR)
A statistical technique for analyzing and developing multiple regressions from data with multiple potential explanatory variables.

prior appropriation
"First in time, first in right." The prevailing doctrine of water rights for the western United States; a legal system that determines water rights by the earliest date of diversion or storage for beneficial use.

probability density function (PDF)
A function, or curve, that defines the shape of a probability distribution for a continuous random variable.

projection
A long-term (typically 10-100 years) forecast of future hydroclimatic conditions that is contingent on specified other conditions occurring during the forecast period, typically a particular scenario of greenhouse gas emissions.

quantiles
Divisions of the range of observations of a variable into equal-sized groups.

r
Correlation coefficient. The strength and direction of a linear relationship between two variables.

R^2
Coefficient of determination. The proportion of variance in a dependent variable that's explained by the independent variables in a regression model.

radiometer
An instrument used to detect and measure the intensity of radiant energy, i.e., shortwave energy emitted from the sun and reflected by clouds, and longwave energy emitted from the earth's surface.

raster
A digital image or computer mapping format consisting of rows of colored pixels.

reanalysis
An analysis of historical climate or hydrologic conditions that assimilates observed data into a modeling environment to produce consistent fields of variables over the entire period of analysis.

reference evapotranspiration
An estimate of the upper bound of evapotranspiration losses from irrigated croplands, and thereby the water need for irrigation.

regression
A statistical technique used for modeling the linear relationship between two or more variables, e.g., snowpack and seasonal streamflow.

relative humidity (RH)
The amount of moisture in the atmosphere relative to the amount that would be present if the air were saturated. RH is expressed in percent, and is a function of both moisture content and air temperature.

remote sensing
The science and techniques for obtaining information from sensors placed on satellites, aircraft, or other platforms distant from the object(s) being sensed.

residual
The difference between the observed value and the estimated value of the quantity of interest.

resolution
The level of detail in model output; the ability to distinguish two points in space (or time) as separate.

> *spatial resolution* - Resolution across space, i.e., the ability to separate small details in a spatial representation such as in an image or model.
> *temporal resolution* - Resolution in time, i.e., hourly, daily, monthly, or annual. Equivalent to time step.

return flow
The water diverted from a river or stream that returns to a water source and is available for consumptive use by others downstream.

runoff
Precipitation that flows toward streams on the surface of the ground or within the ground. Runoff as it is routed and measured within channels is *streamflow*.

runoff efficiency
The fraction of annual precipitation in a basin or other area that becomes runoff, i.e., not lost through evapotranspiration.

sensible heat flux
The flow of heat from the Earth's surface to the atmosphere without phase changes in the water, or the energy directly absorbed/released by an object without a phase change occurring.

shortwave radiation
Incoming solar radiation consisting of visible, near-ultraviolet, and near-infrared spectra. The wavelength spectrum is between 0.2 and 3.0 micrometers.

skew
The degree of asymmetry in a given probability distribution from a Gaussian or normal (i.e., bell-shaped) distribution.

skill
The accuracy of the forecast relative to a baseline "naïve" forecast, such as the climatological average for that day. A forecast that performs better than the baseline forecast is said to have positive skill.

smoothing filter
A mathematical filter designed to enhance the signal-to-noise ratio in a dataset over certain frequencies. Common signal smoothing techniques include moving average and Gaussian algorithms.

snow water equivalent (SWE)
The depth, often expressed in inches, of liquid water contained within the snowpack that would theoretically result if you melted the snowpack instantaneously.

snow course
A linear site used from which manual measurements are taken periodically, to represent snowpack conditions for larger area. Courses are typically about 1,000' long and are situated in areas protected from wind in order to get the most accurate snowpack measurements.

snow pillow
A device (e.g., at SNOTEL sites) that provides a value of the average water equivalent of snow that has accumulated on it; typically the pillow contains antifreeze and has a pressure sensor that measures the weight pressing down on the pillow.

stationarity
The condition in which the statistical properties of the sample data, including their probability distribution and related parameters, are stable over time.

statistically significant
Unlikely to occur by chance alone, as indicated by one of several statistical tests.

stepwise regression
The process of building a regression model from a set of values by entering and removing predictor variables in a step-by-step manner.

stochastic method
A statistical method in which randomness is considered and included in the model used to generate output; the same input may produce different outputs in successive model runs.

stratosphere
The region of the upper atmosphere extending from the top of the troposphere to the base of the mesosphere; it begins about 11–15 km above the surface in the mid-latitudes.

streamflow
Water flow within a river channel, typically expressed in cubic feet per second for flow rate, or in acre-feet for flow volume. Synonymous with **discharge**.

sublimation
When water (i.e., snow and ice) or another substance transitions from the solid phase to the vapor phase without going through the intermediate liquid phase; a major source of snowpack loss over the course of the season.

surface energy balance
The net balance of the exchange of energy between the Earth's surface and the atmosphere.

teleconnection
A physical linkage between a change in atmospheric/oceanic circulation in one region (e.g., ENSO; the tropical Pacific) and a shift in weather or climate in a distant region (e.g., the Colorado River Basin).

temperature inversion
When temperature increases with height in a layer of the atmosphere, as opposed to the typical gradient of temperature decreasing with height.

tercile
Any of the two points that divide an ordered distribution into three parts, each containing a third of the population.

tilt
A shift in probabilities toward a certain outcome.

transpiration
Water discharged into the atmosphere from plant surfaces.

troposphere
The layer of the atmosphere from the Earth's surface up to the tropopause (~11–15 km) below the stratosphere; characterized by decreasing temperature with height, vertical wind motion, water vapor content, and sensible weather (clouds, rain, etc.).

undercatch
When less precipitation is captured by a precipitation gage than actually falls; more likely to occur with snow, especially under windy conditions.

unregulated flow
Observed streamflow adjusted for some, but not all upstream activities, depending on the location and application.

Upper Basin
The parts of the Colorado River Basin in Colorado, Utah, Wyoming, Arizona, and New Mexico that are upstream of the Colorado River Compact point at Lee Ferry, Arizona.

validation
The process of comparing a model and its behavior and outputs to the real system, after calibration.

variance
An instance of difference in the data set. In regard to statistics, variance is the square of the standard deviation of a variable from its mean in the data set.

wavelet analysis
A method for determining the dominant frequencies constituting the overall time-varying signal in a dataset.

Acronyms & Abbreviations

24MS
24-Month Study Model

AET
actual evapotranspiration

AgriMET
Cooperative Agricultural Weather Network

AgWxNet
Agricultural Weather Network

AHPS
Advanced Hydrologic Prediction Service

ALEXI
Atmosphere-Land Exchange Inversion

AMJ
April-May-June

AMO
Atlantic Multidecadal Oscillation

ANN
artificial neural network

AOP
Annual Operating Plan

AR
atmospheric river

AR-1
first-order autoregression

ARkStorm
Atmospheric River 1,000-year Storm

ASCE
American Society of Civil Engineers

ASO
Airborne Snow Observatory

ASOS
Automated Surface Observing System

AVHRR
Advanced Very High-Resolution Radiometer

AWOS
Automated Weather Observing System

BCCA
Bias-Corrected Constructed Analog

BCSD
Bias-Corrected Spatial Disaggregation (downscaling method)

BCSD5
BCSD applied to CMIP5

BOR
United States Bureau of Reclamation

BREB
Bowen Ratio Energy Balance method

C3S
Copernicus Climate Change Service

CA
Constructed Analogues

CADSWES
Center for Advanced Decision Support for Water and Environmental Systems

CADWR
California Department of Water Resources

CanCM4i
Canadian Coupled Model, 4th generation (global climate model)

CBRFC
Colorado Basin River Forecast Center

CCA
Canonical Correlation Analysis

CCSM4
Community Climate System Model, version 4 (global climate model)

CDEC
California Data Exchange Center

CDF
cumulative distribution function

CESM
Community Earth System Model (global climate model)

CFS
Climate/Coupled Forecast System

CFSv2
Coupled Forecast System version 2 (NOAA climate forecast model)

CHPS
Community Hydrologic Prediction System

CIMIS
California Irrigation Management Information System

CIR
crop irrigation requirement

CIRES
Cooperative Institute for Research in Environmental Sciences

CLIMAS
Climate Assessment for the Southwest

CLM
Community Land Model

CM2.1
Coupled Physical Model, version 2.1 (global climate model)

CMIP
Coupled Model Intercomparison Project (coordinated archive of global climate model output)

CNRFC
California-Nevada River Forecast Center

CoAgMET
Colorado Agricultural Meteorological Network

CoCoRaHS
Community Collaborative Rain, Hail and Snow Network

CODOS
Colorado Dust-on-Snow

CONUS
contiguous United States (the lower 48 states)

COOP
Cooperative Observer Program

CP
Central Pacific

CPC
Climate Prediction Center

CRB
Colorado River Basin

CRBPP
Colorado River Basin Pilot Project

CRPSS
Continuous Ranked Probability Skill Score

CRSM
Colorado River Simulation Model

CRSP
Colorado River Storage Project

CRSS
Colorado River Simulation System

CRWAS
Colorado River Water Availability Study
CSAS

CRWAS
Center for Snow and Avalanche Studies

CTSM
Community Terrestrial Systems Model

CU
consumptive use

CUL
consumptive uses and losses

CV
coefficient of variation

CVP/SWP
Central Valley Project/State Water Project

CWCB
Colorado Water Conservation Board

CWEST
Center for Water, Earth Science and Technology

DA
data assimilation

Daymet v.3
daily gridded surface meteorological data

DCP
Drought Contingency Plan

DEM
digital elevation model

DEOS
Delaware Environmental Observing System

DHSVM
Distributed Hydrology Soil Vegetation Model

DJF
December-January-February

DMDU
Decision Making Under Deep Uncertainty

DMI
Data Management Interface

DOD
Department of Defense

DOE
Department of Energy

DOW
Doppler [radar] on Wheels

DRI
Desert Research Institute

DTR
diurnal temperature range

EC
eddy-covariance method

EC
Environment Canada

ECCA
ensemble canonical correlation analysis

ECMWF
European Centre for Medium-Range Weather Forecasts

EDDI
Evaporative Demand Drought Index

EFAS
European Flood Awareness System

EIS
Environmental Impact Statement

En-GARD
Ensemble Generalized Analog Regression Downscaling

ENSO
El Niño-Southern Oscillation

EOF
empirical orthogonal function

EP
Eastern Pacific

ERC
energy release component

ESI
Evaporative Stress Index

ESM
coupled Earth system model

ESP
ensemble streamflow prediction

ESRL
Earth System Research Laboratory

ET
evapotranspiration

ET_0
Reference (crop) evapotranspiration

EVI
Enhanced Vegetation Index

FAA
Federal Aviation Administration

FAWN
Florida Automated Weather Network

FEWS
Famine Early Warning System

FEWS
Flood Early Warning System

FIRO
forecast-informed reservoir operations

FLOR
Forecast-oriented Low Ocean Resolution (global climate model)

FORTRAN
Formula Translation programming language

FPS
Federal Priority Streamgages

FROMUS
Forecast and Reservoir Operation Modeling Uncertainty Scoping

fSCA
fractional snow covered area

FWS
U.S. Fish and Wildlife Service

GCM
global climate model, or general circulation model

GEFS
Global Ensemble Forecast System

GEM
Global Environmental Multiscale model

GEOS
Goddard Earth Observing System (global climate model)

GeoTiff
Georeferenced Tagged Image File Format

GFDL
Geophysical Fluid Dynamics Laboratory

GFS
Global Forecast System model

GHCN
Global Historical Climatology Network

GHCN-D
Global Historical Climate Network-Daily

GHG
greenhouse gas

GIS
geographic information system

GLOFAS
Global Flood Awareness System

GLOFFIS
Global Flood Forecast Information System

GOES
Geostationary Operational Environmental Satellite

GRACE
Gravity Recovery and Climate Experiment

GRIB
gridded binary or general regularly-distributed information in binary form

gridMET
Gridded Surface Meteorological dataset

GSSHA
Gridded Surface/Subsurface Hydrologic Analysis

GW
groundwater

HCCD
Historical Canadian Climate Data

HCN
Historical Climatology Network

HDA
hydrologic data assimilation

HDSC
Hydrometeorological Design Studies Center

HEFS
Hydrologic Ensemble Forecast Service

HESP
Hierarchical Ensemble Streamflow Prediction

HL-RDHM
Hydrologic Laboratory-Research Distributed Hydrologic Model

HMT
Hydromet Testbed

HP
hydrological processor

HRRR
High Resolution Rapid Refresh (weather model)

HSS
Heidke Skill Score

HTESSEL
Land-surface Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land

HUC
Hydrologic Unit Code

HUC4
A 4-digit Hydrologic Unit Code, referring to large sub-basins (e.g., Gunnison River)

HUC12
A 12-digit Hydrologic Unit Code, referring to small watersheds

ICAR
Intermediate Complexity Atmospheric Research model

ICS
intentionally created surplus

IDW
inverse distance weighting

IFS
integrated forecast system

IHC
initial hydrologic conditions

INSTAAR
Institute of Arctic and Alpine Research

IPCC
Intergovernmental Panel on Climate Change

IPO
Interdecadal Pacific Oscillation

IRI
International Research Institute

iRON
Interactive Roaring Fork Observing Network

ISM
Index Sequential Method

JFM
January-February-March

JJA
June-July-August

K-NN
K-Nearest Neighbor

Landsat
Land Remote-Sensing Satellite (System)

LAST
Lane's Applied Stochastic Techniques

LERI
Landscape Evaporative Response Index

lidar
light detection and ranging

LOCA
Localized Constructed Analog

LSM
land surface model

M&I
municipal and industrial (water use category)

MACA
Multivariate Adaptive Constructed Analog

maf
million acre-feet

MAM
March-April-May

MEFP
Meteorological Ensemble Forecast Processor

METRIC
Mapping Evapotranspiration at high Resolution with Internalized Calibration

MJO
Madden-Julian Oscillation

MMEFS
Met-Model Ensemble Forecast System

MOCOM
Multi-Objective Complex evolution

MODDRFS
MODIS Dust Radiative Forcing in Snow

MODIS
Moderate Resolution Imaging Spectroradiometer

MODIS LST (MYD11A2)
Moderate Resolution Imaging Spectroradiometer Land Surface Temperature (MYD11A2)

MODSCAG
MODIS Snow Covered Area and Grain-size

MPR
Multiscale Parameter Regionalization

MRM
Multiple Run Management

MT-CLIM (or MTCLIM)
Mountain Climate simulator

MTOM
Mid-Term Probabilistic Operations Model

NA-CORDEX
North American Coordinated Regional Downscaling Experiment

NAM
North American Monsoon

NAO
North Atlantic Oscillation

NARCCAP
North American Regional Climate Change Assessment Program

NARR
North American Regional Reanalysis

NASA
National Aeronautics and Space Administration

NASA JPL
NASA Jet Propulsion Laboratory

NCAR
National Center for Atmospheric Research

NCCASC
North Central Climate Adaptation Science Center

NCECONET
North Carolina Environment and Climate Observing Network

NCEI
National Centers for Environmental Information

NCEP
National Centers for Environmental Prediction

nClimDiv
new Climate Divisional (NOAA climate dataset)

NDBC
National Data Buoy Center

NDVI
Normalized Difference Vegetation Index

NDWI
Normalized Difference Water Index

NEMO
Nucleus for European Modelling of the Ocean (global ocean model)

NevCan
Nevada Climate-ecohydrological Assessment Network

NGWOS
Next-Generation Water Observing System

NHMM
Bayesian Nonhomogenous Hidden Markov Model

NICENET
Nevada Integrated Climate and Evapotranspiration Network

NIDIS
National Integrated Drought Information System

NLDAS
North American Land Data Assimilation System

NMME
North American Multi-Model Ensemble

NN R1
NCEP/NCAR Reanalysis

NOAA
National Oceanic and Atmospheric Administration

NOAH
Neural Optimization Applied Hydrology

Noah-MP
Noah-Multi-parameterization Model

NOHRSC
National Operational Hydrologic Remote Sensing Center

NPP
Nonparametric paleohydrologic method

NRCS
Natural Resource Conservation Service

NSF
National Science Foundation

NSIDC
National Snow and Ice Data Center

NSMN
National Soil Moisture Network

NVDWR
Nevada Department of Water Resources

NWCC
National Water and Climate Center

NWIS
National Water Information System

NWM
National Water Model

NWP
numerical weather prediction

NWS
National Weather Service

NWSRFS
National Weather Service River Forecast System

NZI
New Zealand Index

OCN
Optimal Climate Normals

OHD
Office of Hydrologic Development

OK Mesonet
Oklahoma Mesoscale Network

ONI
Oceanic Niño Index

OWAQ
Office of Weather and Air Quality

OWP
Office of Water Prediction

PC
principal components

PCA
principal components analysis

PCR
principal components regression

PDO
Pacific Decadal Oscillation

PDSI
Palmer Drought Severity Index

PET
potential evapotranspiration

PGW
pseudo-global warming

PRISM
Parameter-elevation Relationships on Independent Slopes Model

PSD
Physical Sciences Division

QBO
Quasi-Biennial Oscillation

QDO
Quasi-Decadal Oscillation

QM
quantile mapping

QPE
Quantitative Precipitation Estimate

QPF
Quantitative Precipitation Forecast

QTE
Quantitative Temperature Estimate

QTF
Quantitative Temperature Forecast

radar
radio detection and ranging

RAP
Rapid Refresh (weather model)

RAWS
Remote Automated Weather Station Network

RCM
Regional Climate Model

RCP
Representative Concentration Pathway

RE
reduction-of-error

RFC
River Forecast Center

RFS
River Forecasting System

RH
relative humidity

RiverSMART
RiverWare Study Manager and Research Tool

RMSE
root mean squared error

S/I
seasonal to interannual

S2S
subseasonal to seasonal

Sac-SMA
Sacramento Soil Moisture Accounting Model

SAMS
Stochastic Analysis Modeling and Simulation

SCA
snow-covered area

SCAN
Soil Climate Analysis Network

SCE
Shuffled Complex Evolution

SCF
seasonal climate forecast

SE
standard error

SECURE
Science and Engineering to Comprehensively Understand and Responsibly Enhance Water

SFWMD
South Florida Water Management District

SM
soil moisture

SMA
Soil Moisture Accounting

SMAP
Soil Moisture Active Passive

SMHI
Swedish Meteorological and Hydrological Institute

SMLR
Screening Multiple Linear Regression

SMOS
Soil Moisture and Ocean Salinity

SNODAS
Snow Data Assimilation System

SNOTEL
Snow Telemetry

SOI
Southern Oscillation Index

SON
September-October-November

SPoRT
Short-term Prediction Research Transition

SRES
Special Report on Emissions Scenarios

SRP
Salt River Project

SSEBOP
Simplified Surface Energy Balance

SSEBOP ET
Simplified Surface Energy Balance Evapotranspiration

SSP
Societally Significant Pathway

SST
sea surface temperatures

SSW
stratospheric sudden warming

SubX
Subseasonal Experiment

SUMMA
Structure for Unifying Multiple Modeling Alternatives

SVD
singular value decomposition

SW
surface water

SWANN
Snow-Water Artificial Neural Network Modeling System

SWcasts
Southwest Forecasts

SWE
snow water equivalent

SWOT
Surface Water and Ocean Topography

SWS
Statistical Water Supply

Tair
air temperature

Tdew
dew point temperature

TopoWx
Topography Weather (climate dataset)

TVA
Tennessee Valley Authority

UC
Upper Colorado Region (Reclamation)

UCAR
University Corporation for Atmospheric Research

UCBOR
Upper Colorado Bureau of Reclamation

UCRB
Upper Colorado River Basin

UCRC
Upper Colorado River Commission

UCRSFIG
Upper Colorado Region State-Federal Interagency Group

USACE
U.S. Army Corps of Engineers

USBR
U.S. Bureau of Reclamation

USCRN
U.S. Climate Reference Network

USDA
U.S. Department of Agriculture

USGCRP
U.S. Global Change Research Program

USGS
U.S. Geological Survey

USHCN
United States Historical Climatology Network

VIC
Variable Infiltration Capacity (model)

VIIRS
Visible Infrared Imaging Radiometer Suite

VPD
vapor pressure deficit

WBAN
Weather Bureau Army Navy

WCRP
World Climate Research Program

WFO
Weather Forecast Office

WPC
Weather Prediction Center

WRCC
Western Regional Climate Center

WRF
Weather Research and Forecasting

WRF-Hydro
WRF coupled with additional models to represent hydrologic processes

WSF
water supply forecast

WSWC
Western States Water Council

WUCA
Water Utility Climate Alliance

WWA
Western Water Assessment

WWCRA
West-Wide Climate Risk Assessments

WWMPP
Wyoming Weather Modification Pilot Project


WESTERN WATER
ASSESSMENT
A NOAA RISA TEAM
CIRES
University of Colorado Boulder